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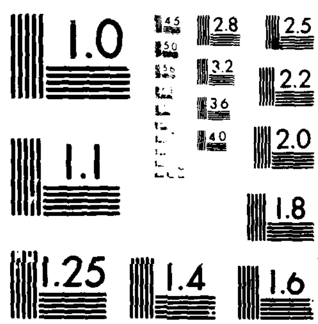

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THERMAL RESPONSE TURBINE SHROUD

General Electric Company
1 Neumann Way
Cincinnati, Ohio 45215

November 1979

AFAPL-TR-79-2108

Final Report for Period 26 September 1978 - 28 September 1979

Air Force Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Thermal Response Turbine Shroud program studied and evaluated overall engine active clearance control designs and payoffs for a broad range of engine/aircraft combinations. Both turbine and compressor active clearance control systems were considered for gas turbine engines that encompassed high and low fan bypass ratios, single and two stage turbines, and commercial and military missions.

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The study of active clearance control included detailed material, heat transfer and thermal and mechanical growth analyses. The study effort looked at the active control of clearances at transient as well as steady state engine operation. The evaluation included an overall assessment of active clearance control benefits and penalties in both performance and cost for the particular aircraft/engine system studied.

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FOREWORD

This final report describes an in-depth study of turbine and compressor Active Clearance Control Systems (ACC) designed for aircraft gas turbine engine applications. The study was conducted by personnel of the General Electric Company, Aircraft Engine Group, Cincinnati, Ohio, under Contract F33615-78-C-2071, Project 3066-10-11, with the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. Charles W. Elrod (AFAPL/TBC) was the Air Force Project Engineer.

The work reported herein was performed in a 12-month period starting in October 1978 and ending in September 1979.

The General Electric Program Manager was E.J. Rogala; the Technical Program Manager was J.E. Sidenstick; the Principal Investigator was C.H. Gay, the author of this report, who wishes to acknowledge the cooperation and assistance of the following individuals for their contribution to this study.

J. Schilling	- Compressor ACC Systems
E.S. Hsia, J. Starkweather	- Turbine Heat Transfer Analysis
E.G. Smith	- Performance Analysis
G.W. Bennett	- Control Systems

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1.0 INTRODUCTION

Continued interest in improving aircraft gas turbine engine performance, fuel usage, reliability, maintainability, and cost establishes the basis for the needed development of new technologies to acquire these benefits. Typically, turbine and compressor blade tip clearances throughout the full range of aircraft/engine usage have a strong influence on engine performance and parts life. Active clearance control offers promising potential for the improvement of current blade tip clearance design technology. However, a study program addressing the optimization of blade tip-to-shroud clearance over the entire engine operating range for a broad mixture of engines and missions was needed to establish a data base for evaluation of active clearance control concepts. Such a study was also needed to identify promising concepts, based on economics and technical feasibility, for future consideration. The study program herein reported is directed at meeting these needs.

1.1 SCOPE

This exploratory development program provides the analyses required to evaluate various active clearance control schemes. The analyses consider the variations of engine design operating conditions and degree of control complexity desired. Both turbine and compressor sections were studied, with emphasis on the turbine section.

The study consisted of five tasks as follows:

Task I - Turbine Concepts Design, Analysis, and Evaluation
Task II - Turbine Heat Transfer Design and Analysis
Task III - Controls Studies
Task IV - Compressor Concepts Design
Task V - Systems Payoff Studies

1.2 OBJECTIVES

The objectives of this program were to evaluate a number of active clearance control concepts, to provide a data base for active clearance evaluation, and to identify promising concepts for further study.

2.0 APPROACH TO CLEARANCE CONTROL

As the initial step in this comprehensive system study of clearance control, the approach was first established. This encompasses the design considerations, the study plan, the control systems, and the system payoff evaluation.

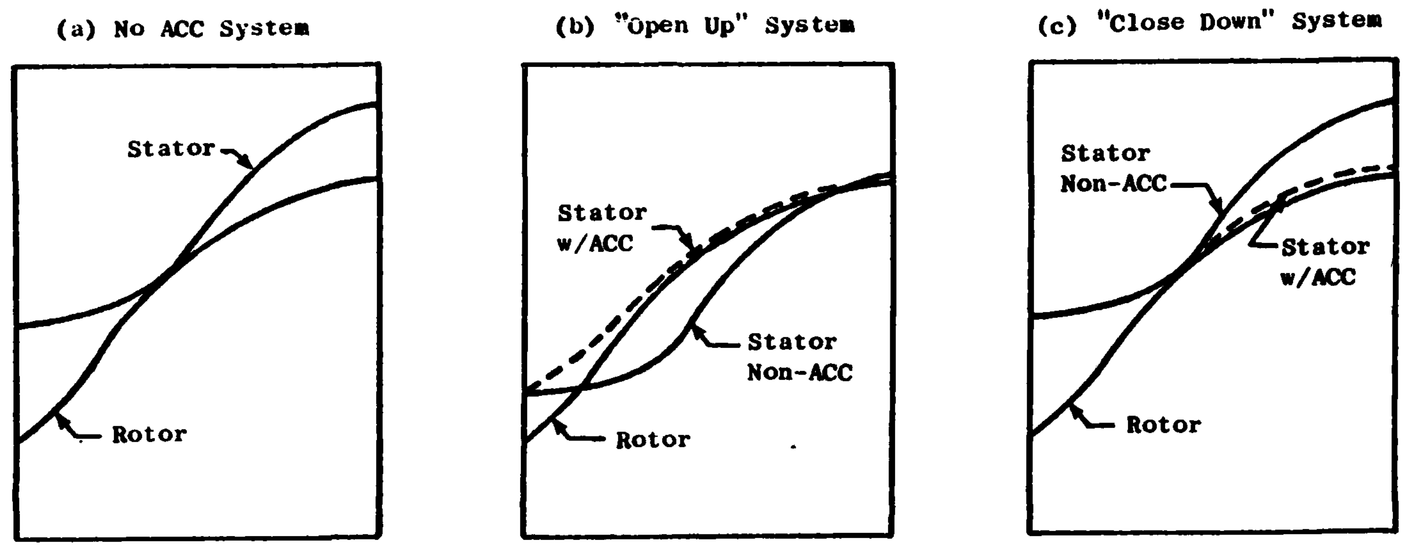
2.1 DESIGN CONSIDERATIONS

In setting the approach for designing a turbine for improved clearances, a system's philosophy was used. Initially, the basic clearance characteristics of typical turbines were researched; fundamental ideas for modifying these characteristics was identified. Then a wide variety of specific concepts were conceived, considerations of positive and negative concept features were weighed, and a single concept was chosen for evaluation in more depth. Achievable clearance improvement was evaluated with the benefit in specific fuel consumption; weighed against engine cycle penalty, and against cost and weight penalties of installation modifications.

A fundamental concept recognized in clearance control work is that the "passive" or natural response characteristics of the system should be made as good as possible prior to the consideration and addition of "active" or forced response systems on the engine. In this definition of active versus passive, the active characteristic is an artificially imposed feature over and above any natural occuring engine response. For example, internal casing heating or external casing cooling that varied during engine operation as a function of normal cycle pressures, etc. would be a passive system. If this heating or cooling were controlled manually or by sensors based on rpm, ambient pressure, etc., it would be an active system. Another major concept is the need for roundness control since oval shroud rings cause blade rubs at their minor axis and cause large effective shroud/blade gaps at the major axis of the oval. These concepts were followed in this program.

2.1.1 Basic Approaches

In looking at the passive engine characteristics, the relative radial growths of the rotor (blade tip) and the stator (static shroud over the blade tip), two basic modification approaches can be taken as shown in Figure 1. An "open-up" system or a "close down" system can be made. This recognizes that for the typical passive system, a large cold rotor/stator clearance is set in order to avoid blade rubs at a transient condition. This usually occurs during takeoff (T/O) or at a chop/accel condition, and is shown schematically in Figure 1(A) at the T/O condition. The result of this transient rub avoidance is that steady-state clearances at low engine power settings are larger than desired.



(a)
- Cold Clearance Set to Avoid Rub at Takeoff/Reburst
- Clearance at Lower Power Settings Higher Than Desired

(b)
- Cold Clearance Set to Give Desired Clearance at Cruise
- ACC System Increases Clea-ance at Higher Power Settings to Avoid Rubs

(c)
- Cold Clearance set to Avoid Rubs at Takeoff
- ACC System Decreases Clearance at Lower Power Settings

Figure 1. Active Clearance Control (ACC) Basic Approaches.

Application of active clearance control to this passive characteristic can be done as shown in either case B or C in Figure 1. The "open up" system [Figure 1(B)] increases stator clearance prior to the anticipated transient rub condition. This gives the desired clearance at steady-state operation (for example, cruise), but causes performance penalties at the transient high power settings.

The "close down" system [Figure 1(C)] uses the same cold clearance as the passive system, thus avoiding transient rubs, but decreases the clearance at steady-state lower power settings.

The major difference between the two systems is that the close down type requires control over the long-time steady-state portions of the engine mission, but fail safe and will not cause inadvertent rubs due to loss of system control. The closure is a reduction in diameter of the stator casing. It is made after the transient rotor diameter changes have occurred (such as takeoff or reburst). Once the steady-state condition, such as cruise, have been reached, the closure is initiated and is held over the entire long-time cruise position of the mission.

This close down system is fail safe in that if during operation at cruise the system should malfunction, its closure action would cease. The casing would grow radially and the blade/casing gap would increase rather than reduce clearances on rubs.

2.1.2 Design Concepts

The many active clearance control (ACC) concepts that were conceived can be categorized by actuation method into the following major headings:.

- Mechanical casing actuation
- Thermal casing actuation
  - Electrical heating
  - Engine air heating/cooling

The application of these concepts depends on the unique geometry and configurations of the turbine and compressor and are discussed in their respective areas.

2.2 STUDY PLAN

The study plan in both the turbine and compressor areas was to conceive and review the possible candidates considering their advantages and disadvantages, and then select a limited number of concepts for further study in more depth.

Concurrent work would be carried out in the heat transfer analysis, mechanical analysis areas while aircraft/engine system analysis and controls system analysis were done. Once temperature distributions were made, clearance calculations could be made. Quantities of air required to obtain minimum clearance could be set. Once the type of control system was selected, the valves and piping could be sized to meet the airflow needed. Weight and cost penalty estimates of the special parts required for ACC could be obtained and, along with clearance performance benefits, could be combined using aircraft/engine performance indexes to determine the net payoffs.

2.3 CONTROL SYSTEM

The control system activity consisted primarily of defining and evaluating control options for the various active clearance control designs being reviewed, and of defining the final control system selected for each engine. The program was broken into three phases:

Phase I - A survey of current programs associated with measurement and control of active clearance control systems.

Phase II - Design study to determine the modification required to identify clearance control systems within the heat transfer design requirements.

Phase III - Weight, cost, and reliability studies to identify the final configuration for each control system.

In each case, a configuration was selected for each engine that would interface with the existing engine control system.

2.3.1 Phase I - Survey of Control Systems

The most promising clearance measurement devices are optical clearance probes. Two methods of measuring clearance with an optical, noncontract, airfoil tip measuring probe have been investigated as follows:

1. Method 1 reflects light off each blade, and the light is caught in a coherent fiber bundle and transmitted into a voltage proportional to clearance (see Figure 2).

2. Method 2 uses an aperture to focus a narrow beam of light which is interrupted by each turbine blade (i.e., the longer the blade the longer the beam is interrupted), and this signal is transmitted into a voltage proportional to clearance (see Figure 3).

Both clearance systems attach the probes to the shroud such that they move with the shroud, hence, the measurement is proportional to clearance.

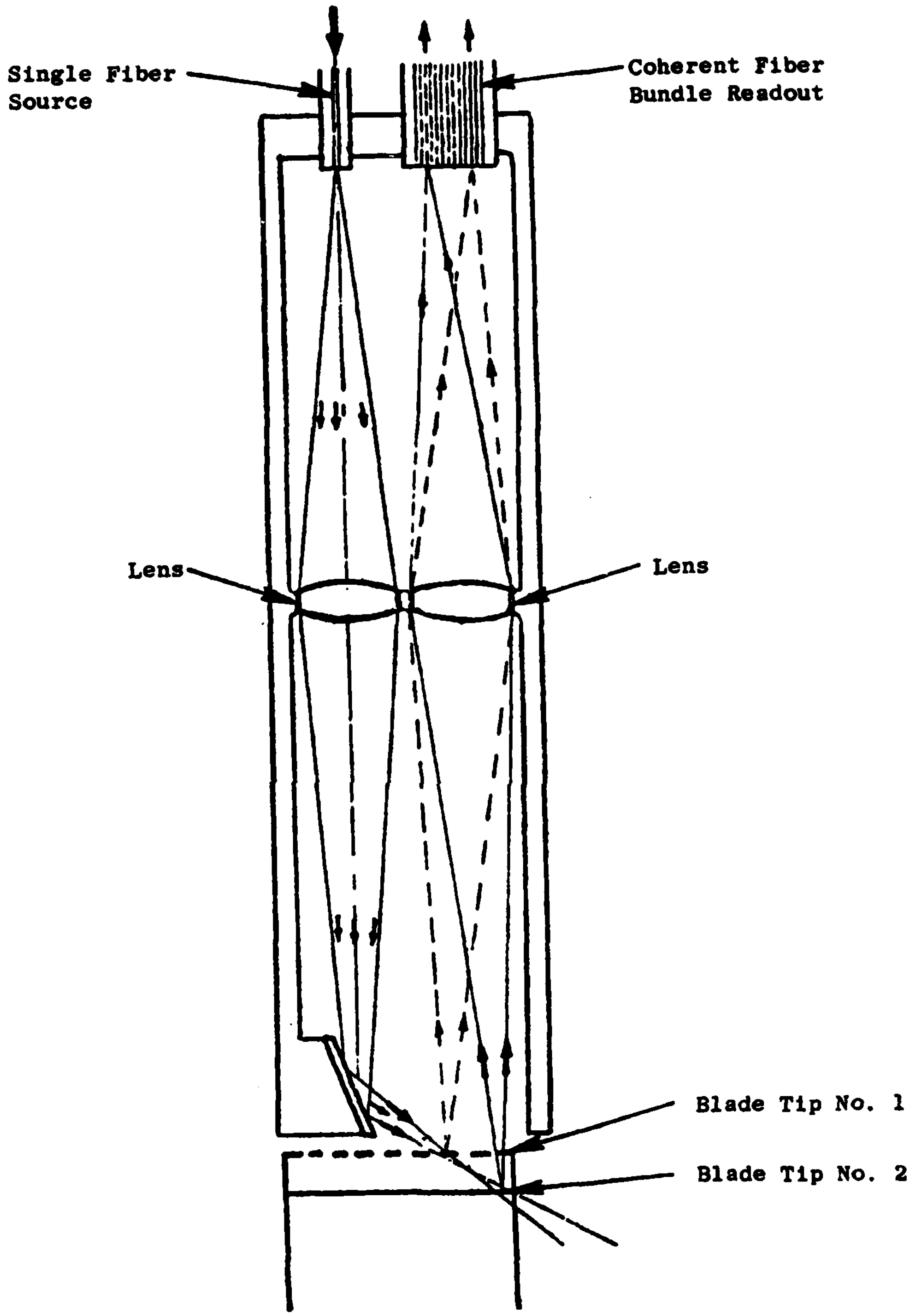


Figure 2. Optical Clearance Probe.

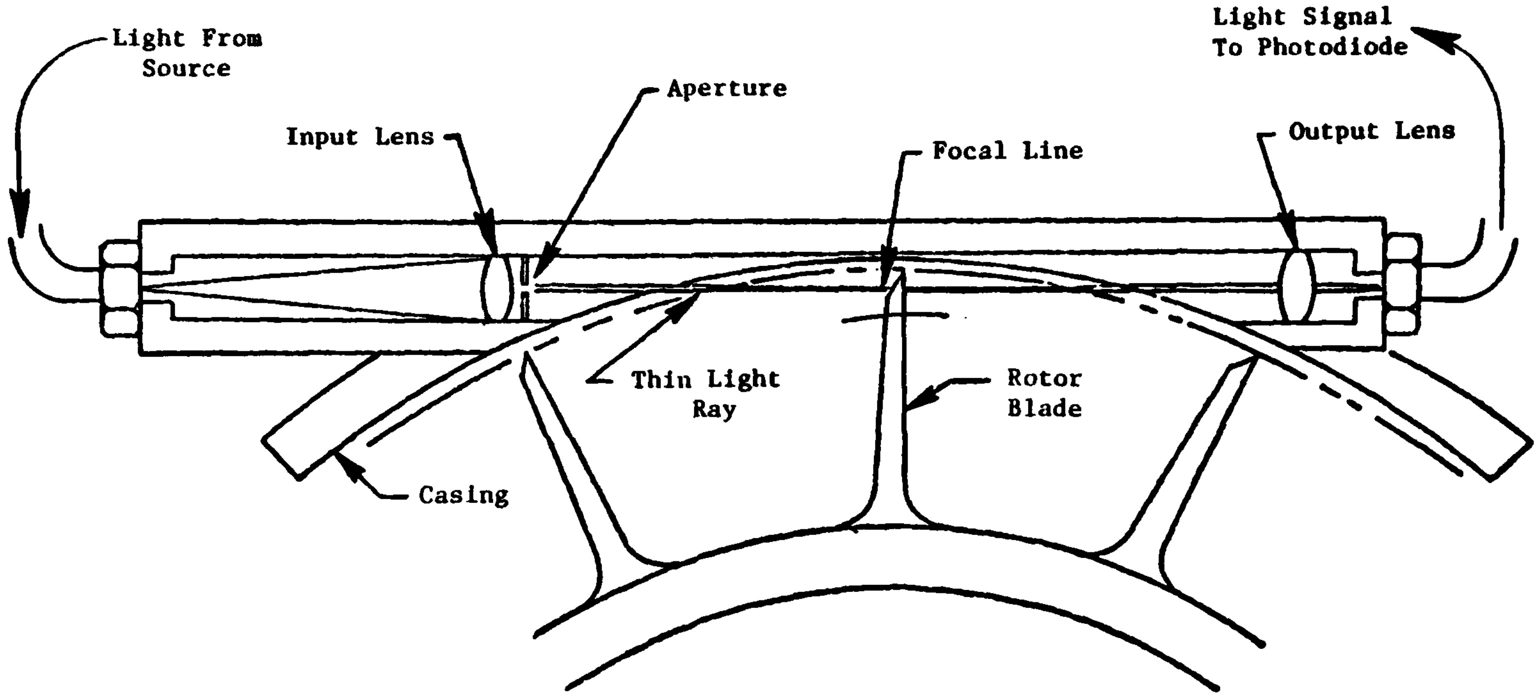


Figure 3. Sensing Concept of Optical Tip Clearance Sensor.

Method 1 has been demonstrated on two YT700-GE-700 engines and on an Avco Lycoming PLT 34 engine. Method 2 is currently being designed and analyzed under a NASA contract. Optical components are to be mounted to a TF34 ninth stage compressor fixture. The majority of the work is experimental and accomplished at GE CR&D, Schenectady. It is expected that the results will be a set of guidelines for an optical tip clearance sensor suitable for design of an engine sensor.

Method 1 is much further along in its development phase in that it has been demonstrated on engine test, however, considerable effort is required in the setup calibration, and use of the system.

The conclusion of this study was that the optical clearance probe position detector, and readout device had been demonstrated; however, significant design work would be required before this device could be used on a production engine.

In the area of nonoptical devices, the CFM56 is the only current GE engine with an active clearance control* that has been engine tested. Two air control valves port either 5th stage or 9th stage compressor air to the HP turbine shroud as a function of core engine speed. Scheduling of this function is accomplished in the hydromechanical fuel control. The air valves are two-position devices which are controlled by fuel actuators.

In the Energy Efficient Engine Program (NASA Contract NAS3-20643), it is planned to calculate actual clearance to schedule the appropriate amount of cooling air to the shroud to maintain the desired clearance.

As a result of the Phase I survey it was decided that separate independent systems be designed for the compressor, HP turbine, and LP turbine. The E^3 control design philosophy was used as the basis for the definition of the preliminary active clearance control system.

Phase II and III control studies were carried out in conjunction with the turbine and the compressor design work and are reported on in these respective sections.

2.4 SYSTEM PAYOFF CALCULATIONS

One of the initial tasks that must be performed in a tradeoff study of this nature is to define the methodology that will be used to evaluate and determine the payoffs for the various systems. The definition of the analysis procedures begin with selection of missions, aircraft types, and engines. The final result is the definition of a system of payoff factors which relates particular figures of merit with the design variables of the system. The sequence of steps required in this procedure as as follows:

*Note definition in Section 2.1.

- Establish missions - aircraft types
- Define engine type
- Perform mission analysis to define engine operating conditions
- Define clearance control system requirements
- Evaluate system performance characteristics, i.e. clearance versus cooling air, etc.
- Select figures of merit for evaluation
- Evaluate sensitivity factors relative to engine and system design factors
- Evaluate and compare studies using the selected figures of merit.

This methodology was used for the evaluation of payoff of numerous clearance control systems when applied to several of the engine components such as fans, compressors, and turbines.

2.4.1 Missions

Initially four general types of aircraft-missions were considered. These include:

- Fighter-Intercept
- Mixed Mission Bomber
- Airborne Warning and Control (AWACS)
- Commercial

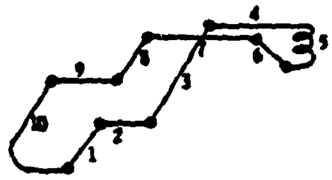
Two missions were defined for the fighter-intercept and mixed mission bomber. Figure 4 shows the air combat and intercept mission. Speed, altitude, power setting, and times are defined for each computer mission. The two bomber missions, supersonic and subsonic penetrate, are given in Figure 5.

The AWACS and commercial missions are shown respectively in Figures 6 and 7.

2.4.2 Engine Types

For these studies, existing or near-term General Electric engines were considered for existing aircraft types. Thus, engine cycle decks were already

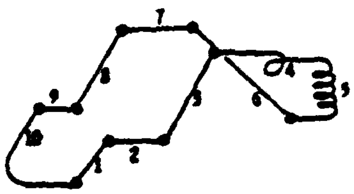
Intercept



	Leg	Alt	Speed	P/S	Time
1.	Takeoff	0	0	Max A/B	0.5
2.	Hold	0-2K	0.50	*	2
3.	Climb	2-30K	0.68	Mil	10
4.	Cruise	30-40K	*	90% RPM	25
5.	Intercept	10-30K	*	Idle-Max A/B	20
6.	Climb	-20K	0.7	Mil	5
7.	Cruise	20K	*	90% RPM	20
8.	Descend	20-10K	*	Idle	0
9.	Loiter	10K	*	80% RPM	5
10.	Land	0	0	Idle-80%	1
					88.5

*To Be Defined By Mission Analysis

Air Combat Maneuver

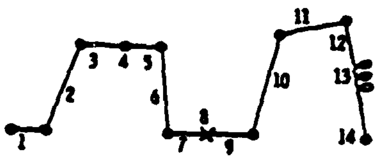


	Leg	Alt	Speed	P/S	Time
1.	Takeoff	0	0	Max A/B	0.5
2.	Hold	0-2K	0.50	*	2
3.	Climb	2-30K	0.68	Mil	10
4.	Cruise	30K	*	90% RPM	20
5.	Combat	5-35K	0.5-0.85	Idle-Max A/B	30
6.	Climb	-35K	0.7	Mil	5
7.	Cruise	35K	*	90% RPM	25
8.	Descend	35-10K	*	Idle	0
9.	Loiter	10K	*	80% RPM	5
10.	Land	0	0	Idle-80%	1
					108.5

* To Be Defined By Mission Analysis

Figure 4. Fighter Intercept Missions.

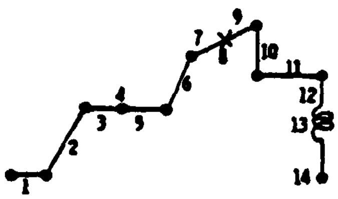
SUBSONIC BOMBER MISSION



Leg	Alt	Speed	P/S	Time
1. Takeoff	0	0	Max A/B	1
2. Climb	0-35K	0.6	Mil	15
3. Cruise	35K	0.8	*	150
4. Refuel	25K	0.8	*	20
5. Cruise	35K	0.8	*	60
6. Descend	35-0K	0.7	Idle	0
7. Penetrate	SL	0.85	*	30
8. Payload	Rel. SL	0.85	*	0
9. Recovery	SL	0.55	*	30
10. Climb		0.6	Mil	15
11. Cruise	45K	0.8	*	70
12. Descend	45-10K	—	Idle	0
13. Loiter	10K	0.4	*	10
14. Land	0	0	Idle-50%	3
				404

*To Be Defined By Mission Analysis

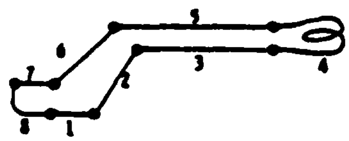
SUPERSONIC BOMBER MISSION



Leg	Alt	Speed	P/S	Time
1. Takeoff	0	0	Max A/B	1
2. Climb	0-35K	0.6	Mil	15
3. Cruise	35K	0.8	*	150
4. Refuel	35K	0.6	*	20
5. Cruise	35K	0.8	*	60
6. Accel-Climb	35-50K	0.8-1.6	Max A/B	4*
7. Penetrate	50K	1.6	*	15
8. Payload	Rel. 50K	1.6	*	0
9. Recovery	50K	1.6	*	15
10. Descend	50-25K	*	Idle	0
11. Cruise	25K	0.7	*	60
12. Descend	25-10K	—	Idle	0
13. Loiter	10K	0.4	*	10
14. Land	0	0	Idle-50%	3
				353

*To Be Defined By Mission Analysis

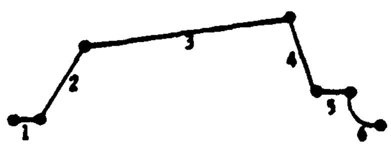
Figure 5. Bomber Missions.



Leg	Alt	Speed	P/S	Time
1. Takeoff	0	0	Mil	2
2. Climb	0-35K	0.5	Mil	15
3. Cruise	35K	0.7	*	60
4. Loiter	20K	0.55	*	600
5. Cruise	35K	0.7	*	60
6. Descend	35-10K	-	Idle	0
7. Loiter	10K	0.4	*	10
8. Land	0	0	Idle-60%	3
				747

*To Be Defined By Mission Analysis

Figure 6. AWACS Mission.



Leg	Alt	Speed	P/S	Time	
1. Takeoff	0	0	Max	1.5	1.5
2. Climb	0-35K	0.6	Max	25	25
3. Cruise	35K	0.84	*	140	240
4. Descend	30-10K	0.7	Idle	0	0
5. Approach	10K	0.5	*	10	10
6. Land	0	0	Idle-80%	3	3
				180	280

*To Be Defined By Mission Analysis

Figure 7. Commercial Missions.

available and aircraft operating characteristics were known. The engine-aircraft combinations selected are as follows:

Mission	Engine	Aircraft
Fighter-Intercept	Two, F101X	F-14
Mixed Mission Bomber	Four, F101	B-1
AWACS	Four, CFM56	E-3A
Commercial	Three, CF6-6	DC-10

During the mission definition and engine selection studies, actual flight power utilization profiles were obtained for a typical fighter-intercept aircraft. Engine power setting versus mission time were as shown in Figure 8. Observations of these profiles show that large, rapid, and frequent throttle excursions are employed, and that steady operation rarely exceeds five minutes. Applicability and payoff for an active clearance control system in this type of mission is questionable. The response of an active control system will be relatively slow because of the large thermal inertias, and controlled clearances are extremely difficult to achieve within these short sustained engine operating times.

For these reasons, studies of clearance control of the F101X engine in a fighter-interceptor were terminated. The study matrix was then selected to include the CFM56, CF6-6, and F101 engine systems.

2.4.3 Mission Analysis

At the initiation of the studies, some cycle data at, a few specific points of interest, were generated for the three study engines. These engine data coupled with aircraft performance characteristics permitted selection of engine operating conditions most suitable for application of clearance control systems.

The specific engine operating conditions for each mission, where sustained operation occurs, is as follows:

Engine	Mission	Mach No.	Altitude	Thrust
F101	Bomber	0.7	20K	4800
CFM56	AWACS	0.7	35K	4052
CFM56	AWACS	0.55	20K	4434
CFM56	Commercial	0.8	36K	3729
CF6-6	Commercial	0.8	36K	6565

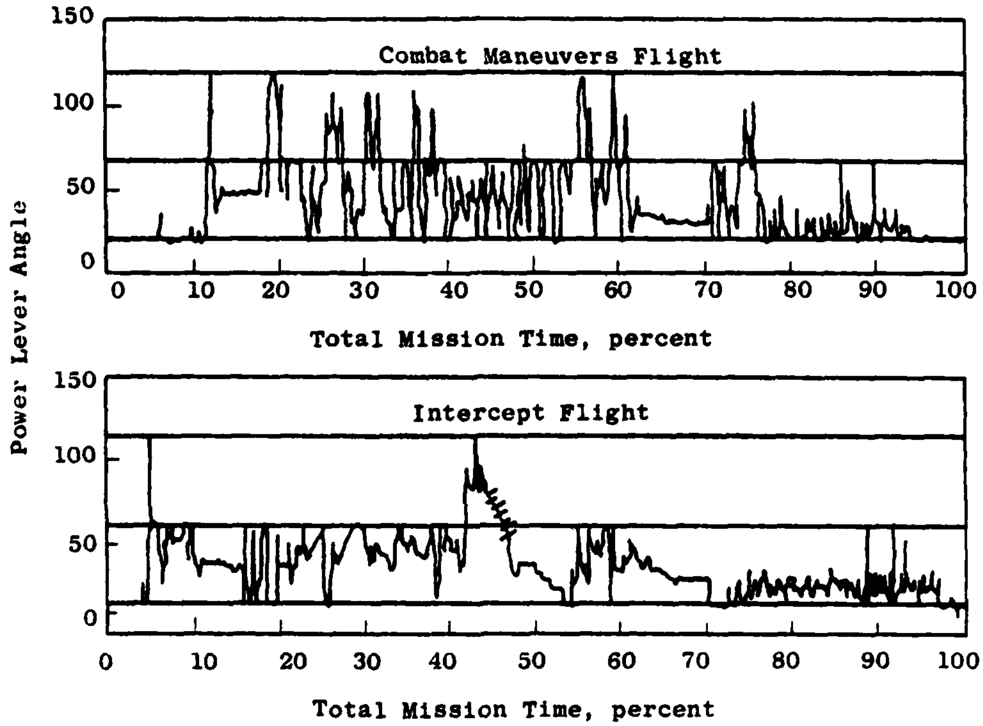


Figure 8. Fighter Mission Profiles.

These cycle conditions were then used to evaluated the payoff for the particular clearance control system. In addition, two other engine operating conditions are critical to the design, but not significant in terms of payoff. These are

- Sea Level Static, Takeoff: for evaluation of turbine temperature overshoot when power settings is increased from idle to take off.

- Maximum Climb, Mach = 0.6, Alt = 20K: for evaluation of clearances during a hot rotor reburst.

2.4.4 Clearance Control Requirements

The clearance control systems would then be designed to meet the following operation conditions:

- Accel from idle to takeoff power at sea level, +27 degrees

- Hot rotor reburst between flight idle and maximum climb at an altitude of 20,000 feet and a Mach number of 0.6

- Maximum effectiveness at the selected cruise power settings given in the previous section.

Cycle data were generated for the three engine systems at these operating conditions to provide data applicable to the design of clearance control systems. Appropriate component operating conditions for the compressor, high pressure turbine, and low pressure turbine for each engine system were calculated.

Active clearance control systems may employ bleed air for control of the component and structure temperatures. The pressures and temperatures at the appropriate engine bleed ports were evaluated. Extraction losses but no manifold or ducting losses were included. The physical flow representative of 1 percent bleed at each location was also calculated.

2.4.5 Engine Sensitivity Factors

The engine system is a device which produces thrust by burning fuel. Cycle calculations determine this propulsive efficiency term. As part of the payoff studies, the engine sensitivity to small changes of component efficiency and engine bleed were determined. The sensitivity factors are also a function of whether the bleed flow is dumped overboard or recouped after application in the clearance control system.

The sensitivity factors are defined as follows:

- Component efficiency sensitivity factor

$$KETA = \frac{\Delta\ SFC/SFC(BASE)}{\Delta\ EFF} = \frac{PCT}{PCT}$$

- Bleed sensitivity factor

$$KBL = \frac{\Delta\ SFC/SFC(BASE)}{\Delta\ BLEED} = \frac{PCT}{PCT}$$

Table 1 gives the engine sensitivity factors for changes of component efficiency and Table 2 gives the data for engine bleed, and derivative data are provided only at the selected flight conditions where the clearance control systems will be activated for long durations.

The payoff factor during the mission cruise leg is improvements in fuel flow. For the takeoff conditions, the figure of merit is normally selected as decrease in turbine inlet temperature overshoot following an acceleration to takeoff power. For this type of evaluation, a different sensitivity factor is required. The factors for the CF6-6 and CFM56 engines are given in Table 3.

2.4.6 Component Efficiency Factors

The previously described sensitivity factors relate engine performance with component efficiency and bleed levels. To close the evaluation loop, factors which relate to the mechanics of the engine are required.

Clearance control systems for three engine components were considered in these studies. Thus, component performance with respect to changes of clearance are required for the high pressure compressor, the high pressure turbine and the low pressure turbine. The sensitivity factor used for relating clearance and component performance is:

$$KCL = \frac{\Delta\ EFF}{\Delta\ Clearance} = \frac{PCT}{MIL}$$

A combination of theoretical analysis and evaluation of existing empirical data were used to establish these sensitivity factors.

2.4.6.1 Compressor

Clearance control of compressors is concerned primarily with the rear stages. The effects of rotor and stator clearance on component efficiency can be predicted using a proven General Electric analytical method. This computer analytical model has been under development since 1962 and is called "The Compressor Unification Study". This mathematical model provides stall pressure ratio capability and design point efficiency potential for a

Table 1. Component Efficiency Sensitivity Factors.

Engine	F101	CFM56	CFM56	CFM56	CF6-6
Mach No.	0.70	0.55	0.70	0.80	0.80
Altitude	20K	30K	35K	36K	36K
Thrust	4800	4434	4052	3729	6565
KETA (HPC)	-0.592	-1.019	-0.941	-0.942	-0.824
KETA (HPT)	-0.810	-1.009	-1.023	-1.004	-0.730
KETA (LPT)	-0.502	-0.776	-0.792	0.772	-0.618

Table 2. Engine Bleed Sensitivity Factors.

Engine	F101	CFM56	CFM56	CFM56	CF6-6
Mach No.	0.70	0.55	0.70	0.80	0.80
Altitude	20K	20K	35K	36K	36K
Thrust	4800	4434	4052	3729	6565
			Dumped		
Fan	+1.261	+1.609	+1.981	+2.286	+1.903
Booster	---	+0.340	+0.396	+0.432	---
Interstage (Stage)	0.874 5	+1.198 5	+1.172 5	+1.205 5	+0.810 8
Interstage (Stage)	---	---	---	---	+1.316 13
Compressor Discharge (Stage)	+1.544 9	+1.806 9	+1.733 9	+1.776 9	+1.617 16
			Recouped		
Interstage (Stage)	+0.274 5	+0.429 5	+0.363 5	+0.371 5	+0.190 8
Interstage (Stage)	---	---	---	---	+0.539 13
Compressor Discharge (Stage)	+0.605 9	+0.965 9	+0.809 9	+0.803 9	+0.729 16

Table 3. Bleed and Efficiency Factors at Sea Level, Takeoff (+27° F).

CF6-6 Engine

	$\Delta T_{41}/\Delta$ (Const NF)	$\Delta T_{41}/\Delta$ (Const FN)
Fan Efficiency	-0.25	-0.18
Booster Efficiency	-0.18	-0.17
Compressor Efficiency	-1.12	-1.12
HP Turbine Efficiency	-1.09	-1.09
LP Turbine Efficiency	-0.28	-0.21
Fan Bleed/No Recoup	-0.07	+0.11
13th Stage Bleed/Recoup	+1.19	+1.19
13th Stage Bleed/No Recoup	+0.95	+0.97
CDP Bleed/Recoup	+0.98	+0.98
CDP Bleed/No Recoup	+0.70	+0.3
CFM56 Engine		
Fan Efficiency	-0.39	-0.47
Compressor Efficiency	-0.87	-0.84
HP Turbine Efficiency	-0.42	-0.40
LP Turbine Efficiency	-0.54	-0.44
Fan Bleed/No Recoup	-0.23	+0.11
5th Stage Bleed/No Recoup	+0.81	+0.85
CDP Bleed/No Recoup	+1.07	+1.103

multistage compressor. Compressor design parameters such as blade speed, axial velocity, reaction (swirl level), solidity, aspect ratio, Reynold's number, and clearance are considered in this analysis.

The analytical method was employed to predict the clearance derivatives (KCL) for the F101 and CF6-6 compressors. Stages 6-9 were considered for the F101 and stages 12-16 for the CF6-6. Note that the F101 and CFM56 compressors are very similar and a single set of sensitivity factors apply to both configurations. The trends of compressor efficiency with changes of rotor clearance, stator clearance, and combined rotor-stator clearance were determined at compressor design conditions and were assumed to be applicable at any other compressor operating condition. Table 4 gives these compressor clearance factors.

2.4.6.2 High Pressure Turbines

During these studies, two types of high pressure turbines were considered. The F101 and CFM56 engines have single-stage unshrouded, high pressure turbines. The CF6-6 has a two-stage, unshrouded turbine. Performance of these turbines are sensitive to clearance at the rotor tip and clearance of the interstage stator seals.

The sensitivity of turbines to rotor tip clearance is based on an emperical correlation of data derived during tests of numerous turbines with different levels of clearance. The accepted factors for clearance effects are as follows:

- One-stage HP turbines, unshrouded

  ΔETA/ΔCL = 1.8 POINTS/PERCENT

- Two-stage HP turbines, unshrouded

  ΔETA/ΔCL = 1.6 POINTS/PERCENT

Effects of stator or vane seal clearance were evaluated by simply accessing the level of flow leakage using labyrinth seal data. This analysis method considers seal pressure ratio, number of seal teeth, stationary seal geometry, and seal radial clearance. Leakage trends and thus efficiency levels are nonlinear with actual radial clearance.

Typical efficiency trends with clearance for the two-stage CF6-6 turbine are shown in Figure 9. Sensitivity factors for the single-stage turbine of the F101 and CFM56 engines are given in Figure 10. Application of these factors to pay off studies is simplified if constant differentials are assumed. Such linearized factors are given in Table 5 for the high pressure turbines considered in these studies.

Table 4. Compressor Clearance Sensitivity Factors.

Compressor	Stages	Rotor	Stator	Combined*
F101 and CFM56	6-9	0.0112	0.0056	0.0161
CF6-6	12-16	0.0058	0.0034	0.0088

*KCL is given in Points/Mil/Stage

Table 5. HP Turbine Clearance Sensitivity Factors.

Engine	Turbine Type	Blade Row	KCL (Points/Mil)
F101, CFM56	HP	Rotor 1	0.101
CF6-6	HP	Rotor 1	0.036
		Rotor 2	0.021
		Vane 2	0.012

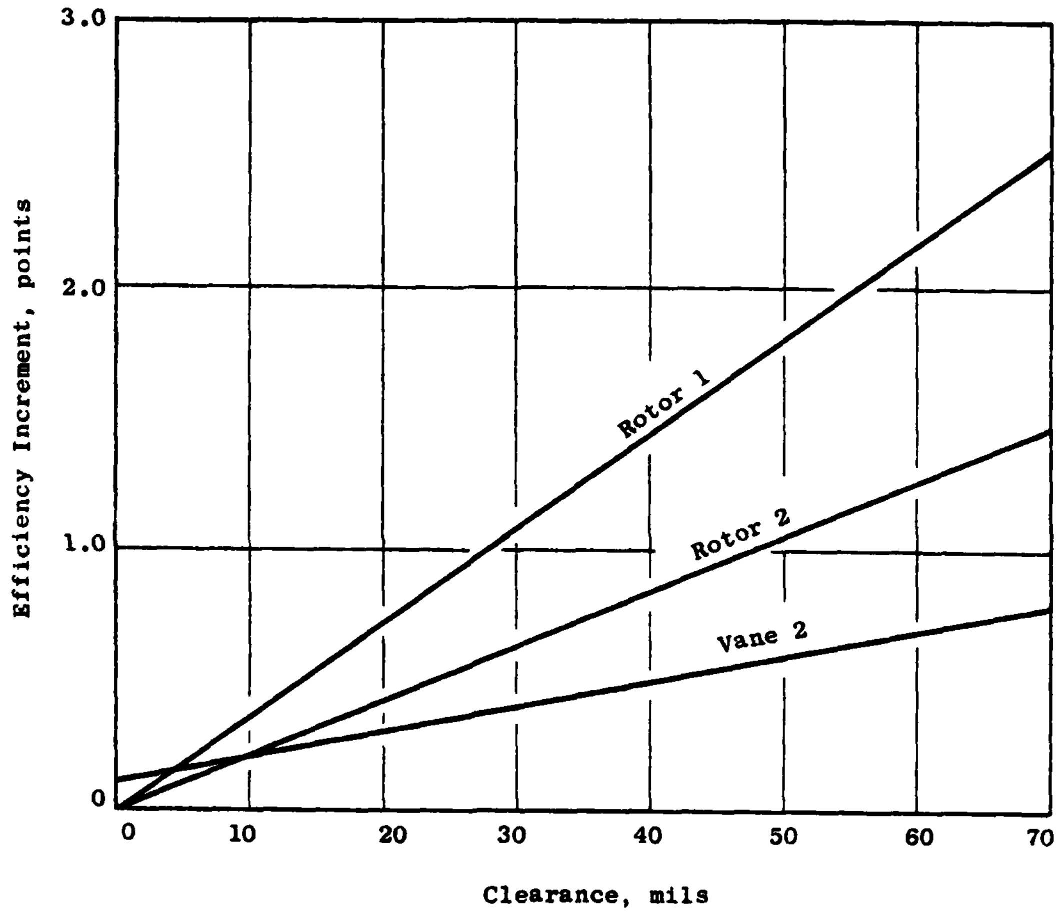


Figure 9. CF6-6 HP Turbine Sensitivity Factors.

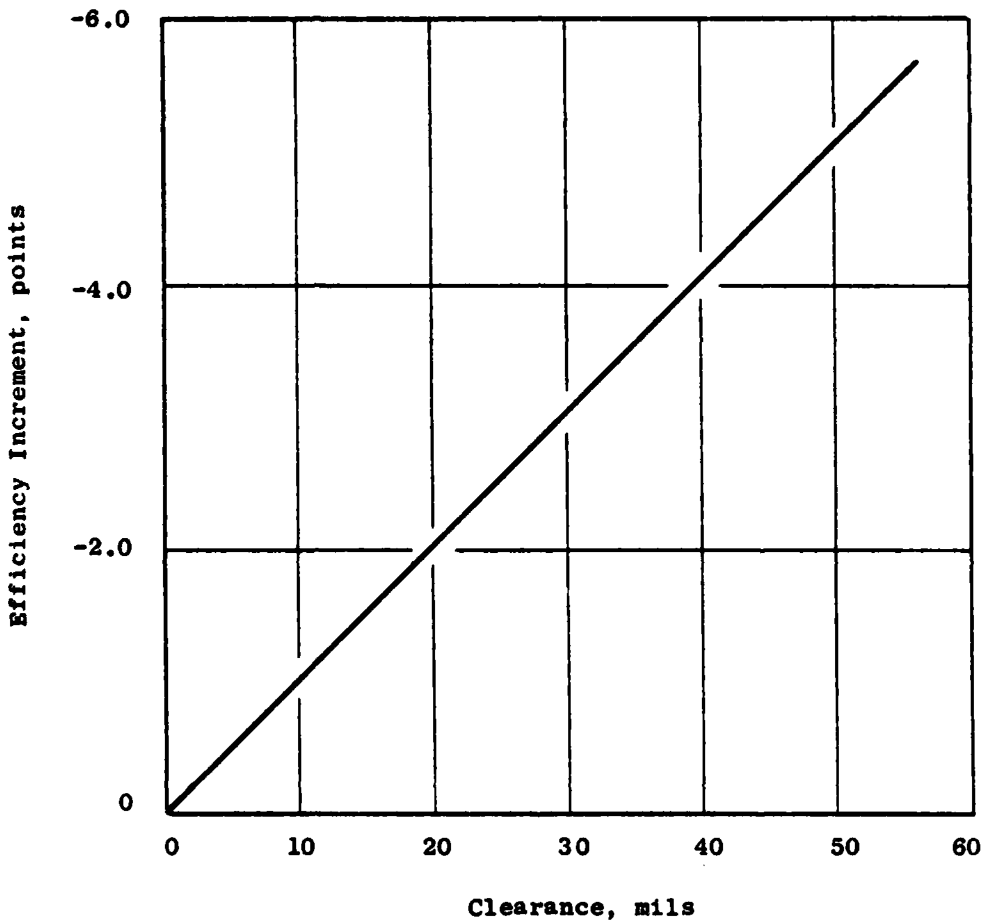


Figure 10. F101 and CFM56 HP Turbine Sensitivity Factors.

2.4.6.3 Low Pressure Turbines

The two low pressure turbines that were candidates for clearance control analysis were in CFM56 and CF6-6 engines. Both of these turbines employ shrouded rotors, the CFM56 having four stages and the CF6-6 having five stages. Performance losses due to seal leakage for these turbines are treated similar to interstage seals, using labyrinth seal data. Percent flow leakage is treated as a percent loss in energy extraction and thus a similar reduction in stage efficiency. Figure 11 presents the sensitivity factors for the CF6-6 engine and Figure 12 gives similar data for the CFM56 engine. Assuming approximate linear relationships, the sensitivity factors in derivative notation are listed in Table 6.

2.4.7 Payoff Factors

There are many different factors which can be used to establish the payoff for a particular modification to a propulsion system. In this study, the three particular missions and aircraft combinations were selected to evaluate three different figures of merit (FOM) for payoff.

Payoff Figure of Merit	Mission
Range	Bomber
Time-on-Station	AWACS
Direct Operating Costs	Commercial

The three engine factors which contribute to the payoff are fuel, engine weight, and cost for the commercial mission. Only fuel and engine weight add to the other two factors.

Thus, a set of sensitivity factors can be selected to relate the FOM and engine paramenters.

- Fuel Flow (ΔSFC)

$$KSFC = \frac{\Delta\ FOM}{\Delta\ SFC} = \frac{PCT}{PCT}$$

- Engine Weight (ΔENG WT)

$$KWT = \frac{\Delta FOM}{\Delta ENG\ WT} = \frac{PCT}{PCT}$$

- Engine Cost (ΔENG COST)

$$KCOST = \frac{\Delta FOM}{\Delta ENG\ COST} = \frac{PCT}{PCT}$$

The total effect of a particular engine configuration change can thus be written as follows:

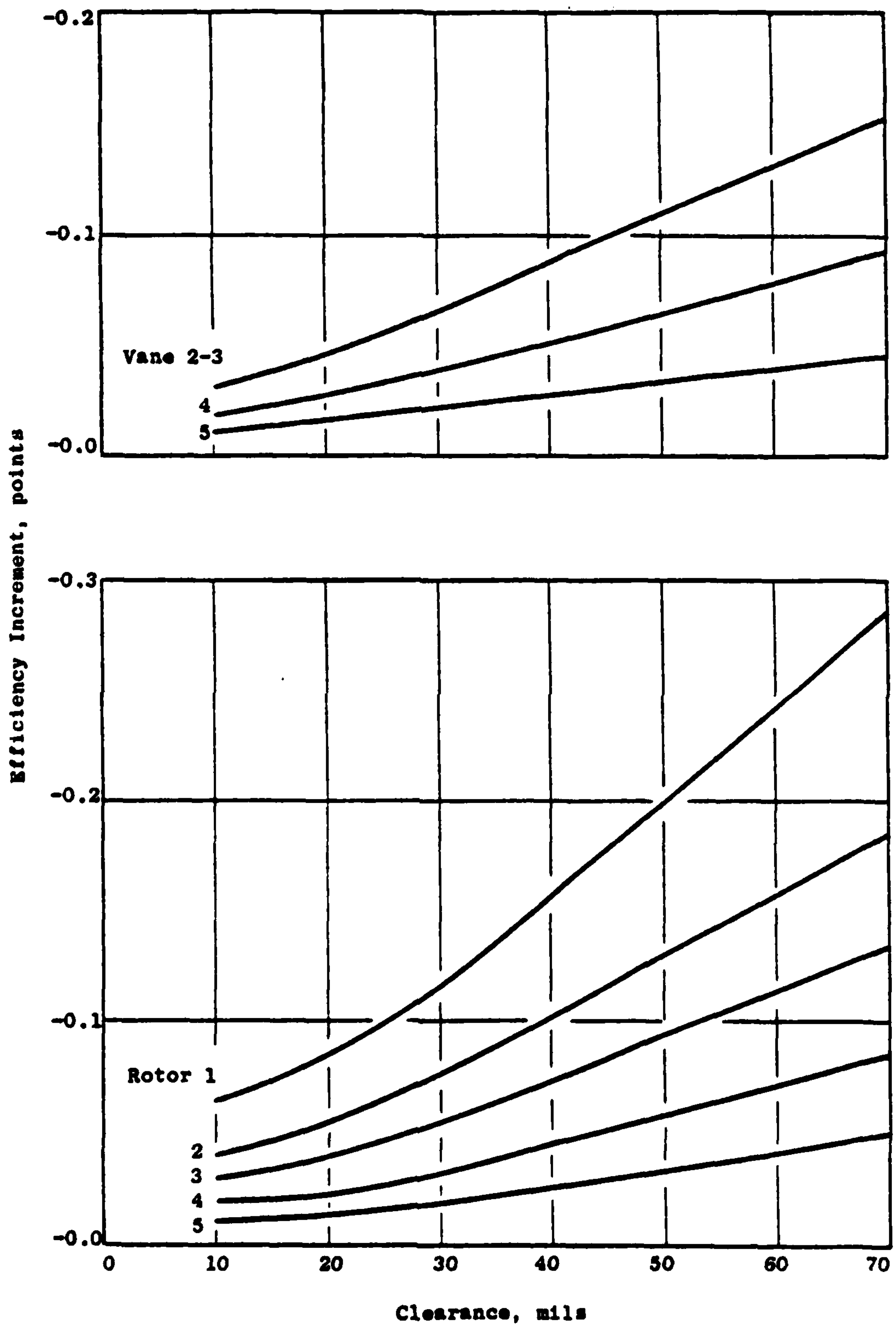


Figure 11. CF6-6 LP Turbine Sensitivity Factors.

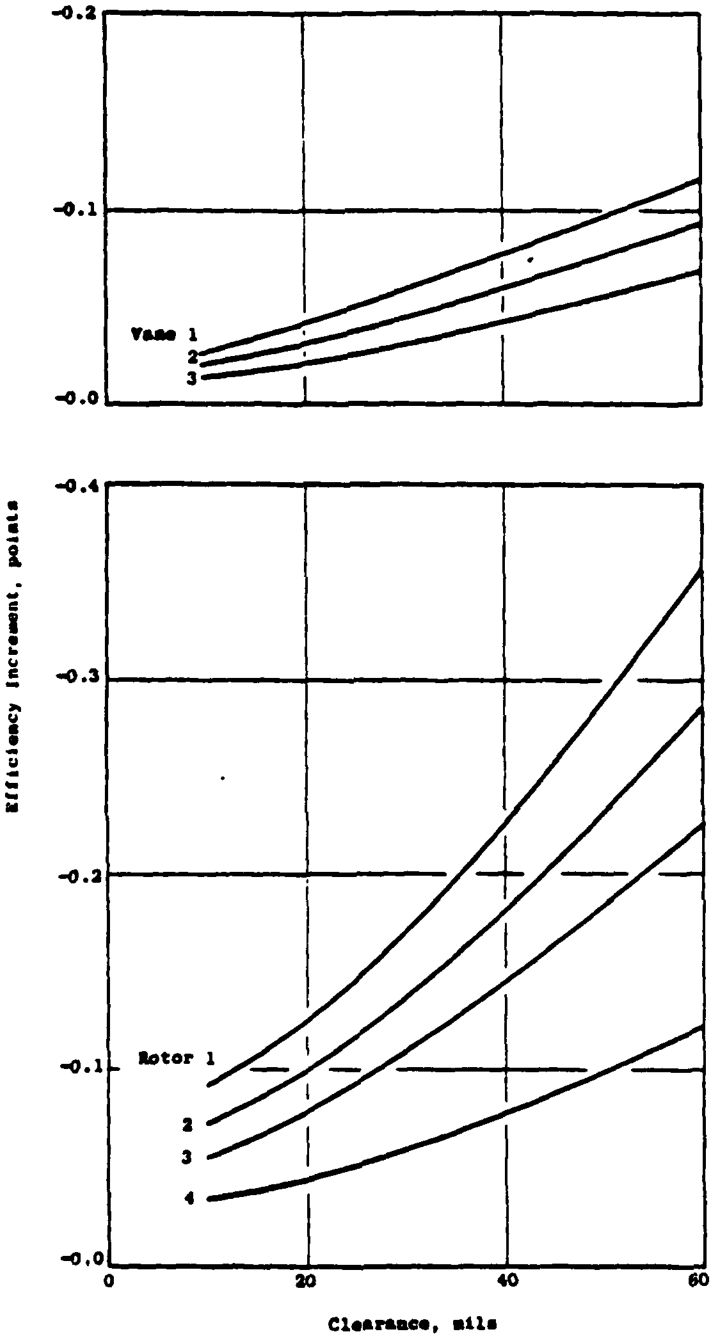


Figure 12. CFM56 LP Turbine Sensitivity Factors.

Table 6. LP Turbine Clearance Sensitivity Factors.

Engine	Turbine Type	Blade Row	KCL (Points/Mil)
CFM56	LP	Rotor 1	0.0063
		Rotor 2	0.0050
		Rotor 3	0.0040
		Rotor 4	0.0022
		Vane 2	0.0019
		Vane 3	0.0015
		Vane 4	0.0011
CF6-6	LP	Rotor 1	0.0042
		Rotor 2	0.0027
		Rotor 3	0.0020
		Rotor 4	0.0013
		Rotor 5	0.0008
		Vane 2	0.0022
		Vane 3	0.0022
		Vane 4	0.0014
		Vane 5	0.0006

Table 7. Payoff Sensitivity Factors.

Factor	Mission		KCOST	KWT	KSFC
ΔRange	Mixed Mission Bomber				
	- 4 F101 Engines		N/A	-0.072	-0.392
ΔTime-on-Station	AWACS				
	- 2 CFM56 Engines	Cruise	N/A	-0.17	-0.27
		Loiter	N/A	-0.17	-1.00
ΔDOC	Commercial				
	- 4 CFM56 Engines, 2500 mi. Mission		+0.100	+0.026	+0.397
	- 3 CF6-6 Engines, 1500 mi. Mission		+0.085	+0.022	+0.364

$$FOM = KWT^{*} (\Delta ENG\ WT) + KCOST^{*}(\Delta ENG\ COST) + KSFC^{*} (\Delta SFC)$$

The previous discussions have defined the parameters of a clearance control which contribute to changes in the fuel flow or specific fuel consumption. The sfc term is then a function of two other variables

$$\Delta SFC = KETA^{*}KCL^{*}\Delta CL + KBL^{*}\Delta BL$$

For evaluation of the payoff with a particular clearance control configuration, the total change of FOM is related to the clearance change in 1000th's of an inch, ΔCL; the amount of % bleed flow required, ΔBL; and engine characteristics such as weight and cost.

The factors KETA and KBL, relating the engine component efficiency and fuel consumption, have been defined in the previous discussions. The sensitivity factors KWT, KCOST, and KSFC require definition for each of the aircraft-mission configurations. The figures of merit, such as range and time-on-station, are influenced by engine fuel consumption and weight only; cost is not a contributing factor. Direct operating costs for the commercial aircraft are influenced by all three engine parameters.

The sensitivity factors KWT, KCOST and KSFC are given in Table 7 and were obtainedd using available data from studies of the following:

- B-1 Bomber
- 1977 airline operating costs for 707, 747, and DC-10 aircraft
- Operating characteristics of E-3A aircraft.

For evaluation of the figure of merit (range) of the bomber, previous studies of a four-engine B-1 type bomber were used. These studies considered the subsonic and supersonic missions, and then evaluated the change of range with respect to engine weight and fuel consumption. The factors are the same for both missions and are 23.5 miles change of range per percent change in sfc and 4.3 miles change of range per percent change of engine weight. For a typical 6000 mile mission range, the sfc factor and weight factors are as follows:

$$KSFC = \left[\frac{23.5}{6000}\right] X \quad 100 = 0.392$$

$$KWT = \left[\frac{4.3}{6000}\right] X \quad 100 = 0.072$$

The fuel sensitivity factors for the AWACS mission can be evaluated in a relatively direct manner because the mission is flown at a nearly constant engine power setting. The fuel sensitivity factor at loiter is one percent fuel saved from one percent time-on-station. Thus, the factor KSFC at loiter is equal to 1.0. Sensitivity for the cruise out and return legs are approximately equal to the percent fuel used during these two mission legs. Through analysis of the mission, the actual factor was derived to be 0.27 percent change in time-on-station per percent change of fuel flow. Using a mission analysis and aircraft-engine fuel breakdown for the two-engine, E-3C, the engine weight sensitivity factor was established to be 0.17.

The figures of merit for the commercial missions were evaluated for a 2500 mile mission using a 707-type aircraft with four CFM56 engines. The 1500 mile mission was flown using a DC-10 aircraft with three CF6-6 engines. Aircraft operating costs during 1977 were used as a basis for these studies. Fuel costs as a percent of total operating costs can be determined as a function of trip length. Fuel saving payoff increases with increased trip length as shown in Table 7.

A relative comparison of the payoff sensitivity factors in Table 7 can be made, but care must be taken to compare similar factors. For example, ΔDOC can be compared between the two commercial missions, but ΔDOC versus Δrange or versus Δ time-on-station comparisons would be incorrect and misleading. With this in mind, a review of the KCOST column shows the four-engine commercial aircraft has a larger value which reflects the larger engine cost as a percentage of total aircraft cost. Similarly, the KWT column reflects the engine weight as a percentage of total aircraft weight.

The KSFC factor comparison should be made within groups; for the commercial and for the AWACS mission. Under commercial, the longer cruise leg of the 2500 mile flight has a larger sfc effect and thus gives a higher payoff factor. Under AWACS, the loiter portion of the mission is such a large percentage that the loiter KSFC factor far exceeds that of the cruise factor.

In order to use this evaluation procedure, the following engine parameters must be determined through design studies:

- Change of operating clearances at the cruise operating point
- Location and level of bleed required to achieve this clearance change
- Added engine manufacturing costs for the changes
- Added engine weight.

Combining these parameters and the sensitivity factors will yield a level of payoff. Improvements in range and time-on-station are indicated by positive levels of payoff. A negative value of ΔDOC represents improved operation.

The application of this method will be described in each section covering the studies of a particular engine component.

3.0 TURBINE

The analysis of the turbine clearances consisted first of concept analysis and selection where a variety of possible configurations were screened, and next of specific evaluation of the CFM56/F101 and the CF6-6.

3.1 CONCEPT ANALYSIS AND SELECTION

3.1.1 Mechanical Actuation

Two mechanical actuation configurations (Concepts No. 1 and No. 2) were examined which consisted of a cam system that displaced either a vertical or horizontal shell in order to move the shrouds up or down. The advantages of these concepts were their fast response time and that no power was required over the long time cruise portions of the aircraft mission. Disadvantages were the large number of moving parts, its best utilization required a clearance sensing system, high stress/low life concerns in the flexible shells, fail-safe operation would require positive indexing, potential out-of-round from partial cam misposition, potential out-of-round ray of thin shells, and concern for seal integrity.

3.1.2 Thermal System/Electrical Heating

An "open up" system utilizing electrical heating has been identified in a prior program and was reviewed here in the No. 3 configuration shown in Figure 13. This concept employs an electrical heating element to enlarge the shroud support diameter during transient operation (before or during takeoff, or at throttle burst). The advantages of this system are the simple configuration with its few parts and no need for power over the long-time steady-state mission points. The disadvantages are the large amperage requirement at transient points, the attendant oversize electrical supply (weight, cost, volume penalties), and the lack of a fail-safe capability (without severe rubs).

3.1.3 Thermal System/Electrical Heating and Compressor Cooling

A modification of the prior system utilizes electrical heating supplemented by compressor cooling air. The No. 4 approach here is to achieve outward shroud motion through electrical heating of the shroud ring and to obtain inward shroud motion through interstage compressor air cooling of the ring. The advantage here is the lower electrical power requirement compared with the all electrical system. This occurs due to the lower heating demand as shown in Figure 14. As seen, the desired shroud motion can be related to a required ΔT range. This range can be achieved by several methods - either all heating, all cooling, or a combination of heating and cooling. Since the electrical-type system provides heating, an all electrical concept must provide the full

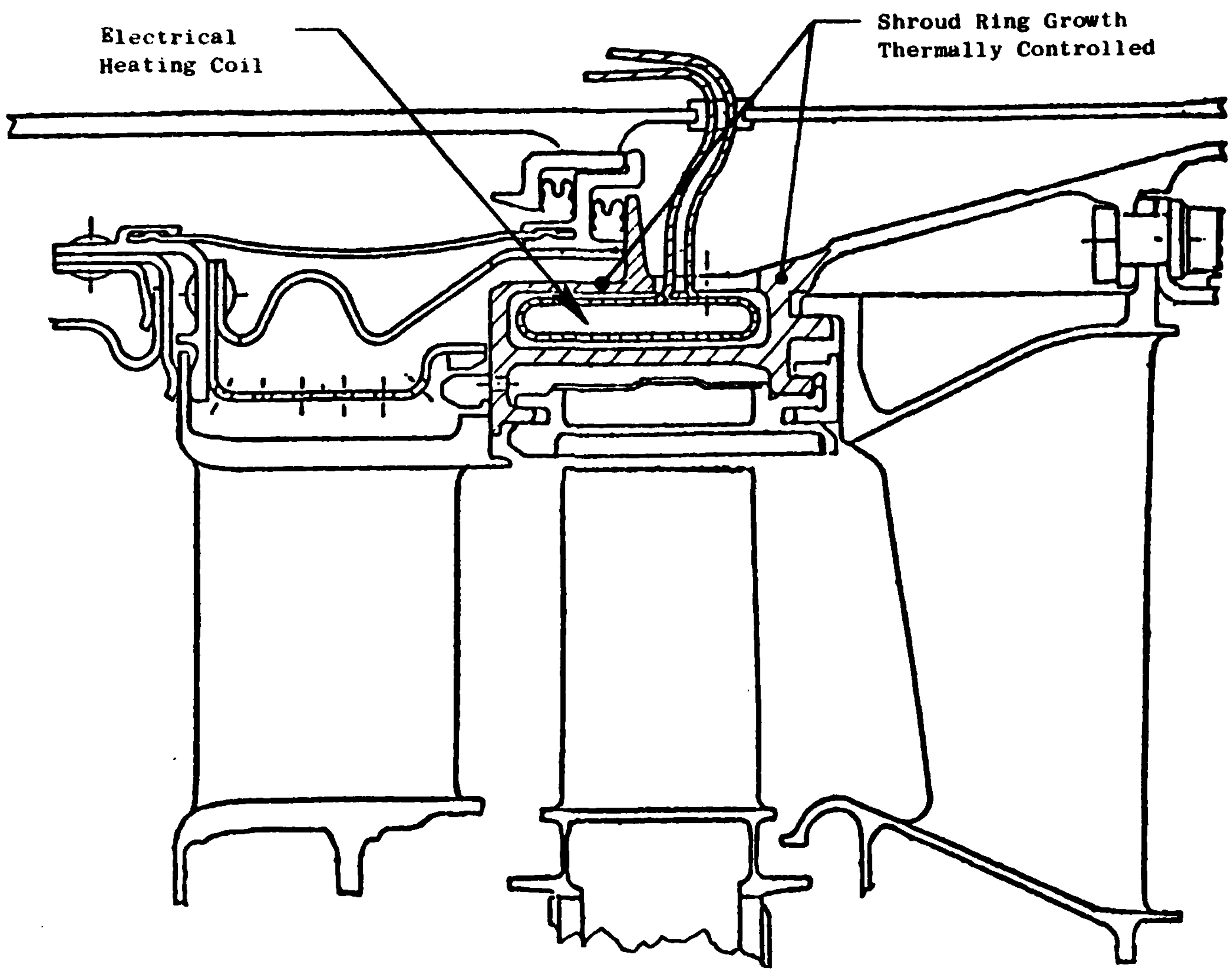


Figure 13. Electrical ACC Heating, Concept Number 3.

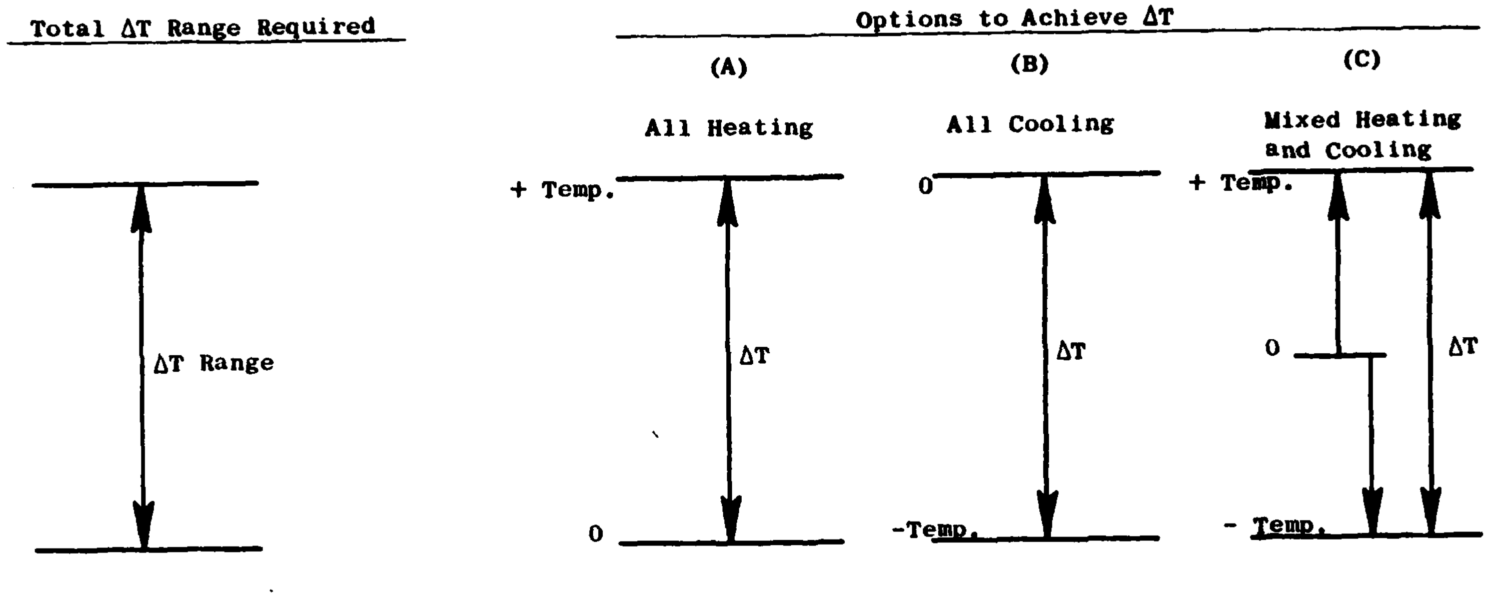


Figure 14. Thermal Demand for Total ΔT Range Required and Options to Achieve ΔT.

ΔT range while a partial electrical concept need only supply the portion of the full ΔT not provided by the cooling source. Disadvantages are the engine geometry must be compatible with both the air and the electrical systems, reasonably high amperage is still required, it is not fail safe in avoiding rubs, and there is a cycle penalty at steady-state operation due to coolant bleed from the compressor.

3.1.4 Thermal System/Compressor Cooling and Heat Exchanger

Concept No. 5 uses compressor bleed air for cooling and is supplemented by a heat exchanger to provide a heating function. Interstage compressor air (5th Stage) is used for direct cooling on shroud rings for radial shrinkage while compressor discharge pressure (CDP) air is used indirectly to heat the interstage air by means of an interstage/CDP heat exchanger as shown in Figure 15. The heating is used only during engine transient operation. The advantages of this concept are the elimination of the electrical system cost, weight, and customer interface; and the relatively simple installation and piping. The major disadvantages are the complexity and weight of the heat exchanger, the non-fail-safe characteristic of the heat exchanger (in preventing rubs), and the cycle penalty of compressor bleed used at steady-state operation.

3.1.5 Thermal System/Variable Direct Air: Fan, CDP

Another system using only air for clearance control (as do Concepts 5 and 7) is shown as Concept No. 6 in Figure 16. Two sources of air, fan and compressor discharge air, are used to provide the largest possible air source thermal differences which acts on the internal shroud support rings to control shroud radial clearance. The advantages offered by this concept, as compared to the prior systems, are the cold fan air allows a greater ring closure than 5th stage air, the larger source ΔT also allows faster response time, and no customer interface is required as would be for extra electrical power. The disadvantages are the performance penalty to the cycle due to air bleed from the compressor and more complex piping and valving than a system which uses a single air source.

3.1.6 Thermal System/Variable Direct Air: 13th Stage, CDP

As shown in Figure 17, Concept No. 7, which was identified in a prior program and reviewed here, is very similar to the fan/CDP system (Figure 16) but with the following differences. Piping weight and complexity are less than in Concept No. 6 since CDP is utilized internally rather than externally and all external piping can be eliminated. Response time and amount of clearance change are less due to the small ΔT between air sources. Cycle penalties are potentially larger since expended 13th stage air is a greater energy loss than fan air.

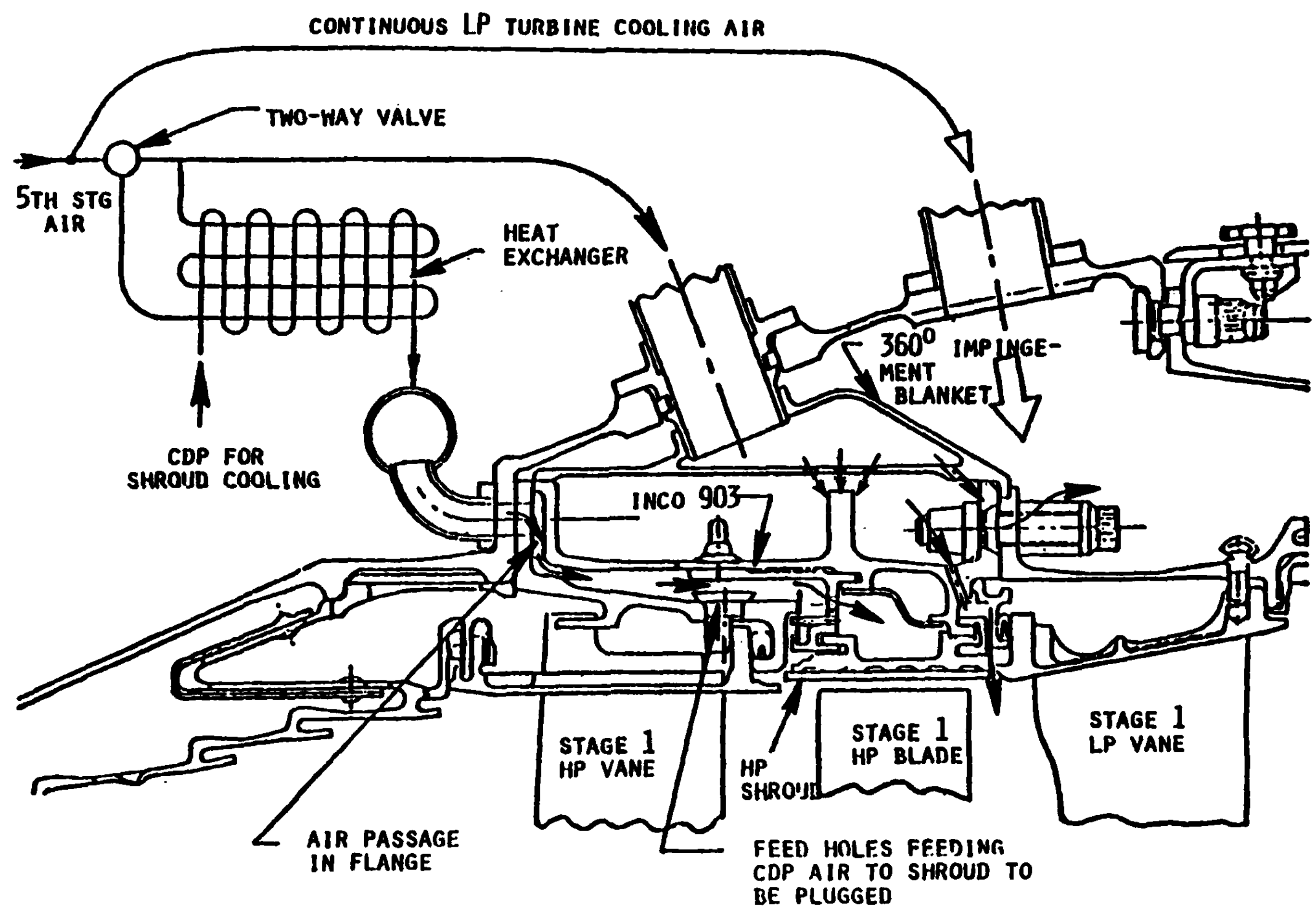


Figure 15. Heat Exchanger Plus Compressor Bleed, Concept Number 5.

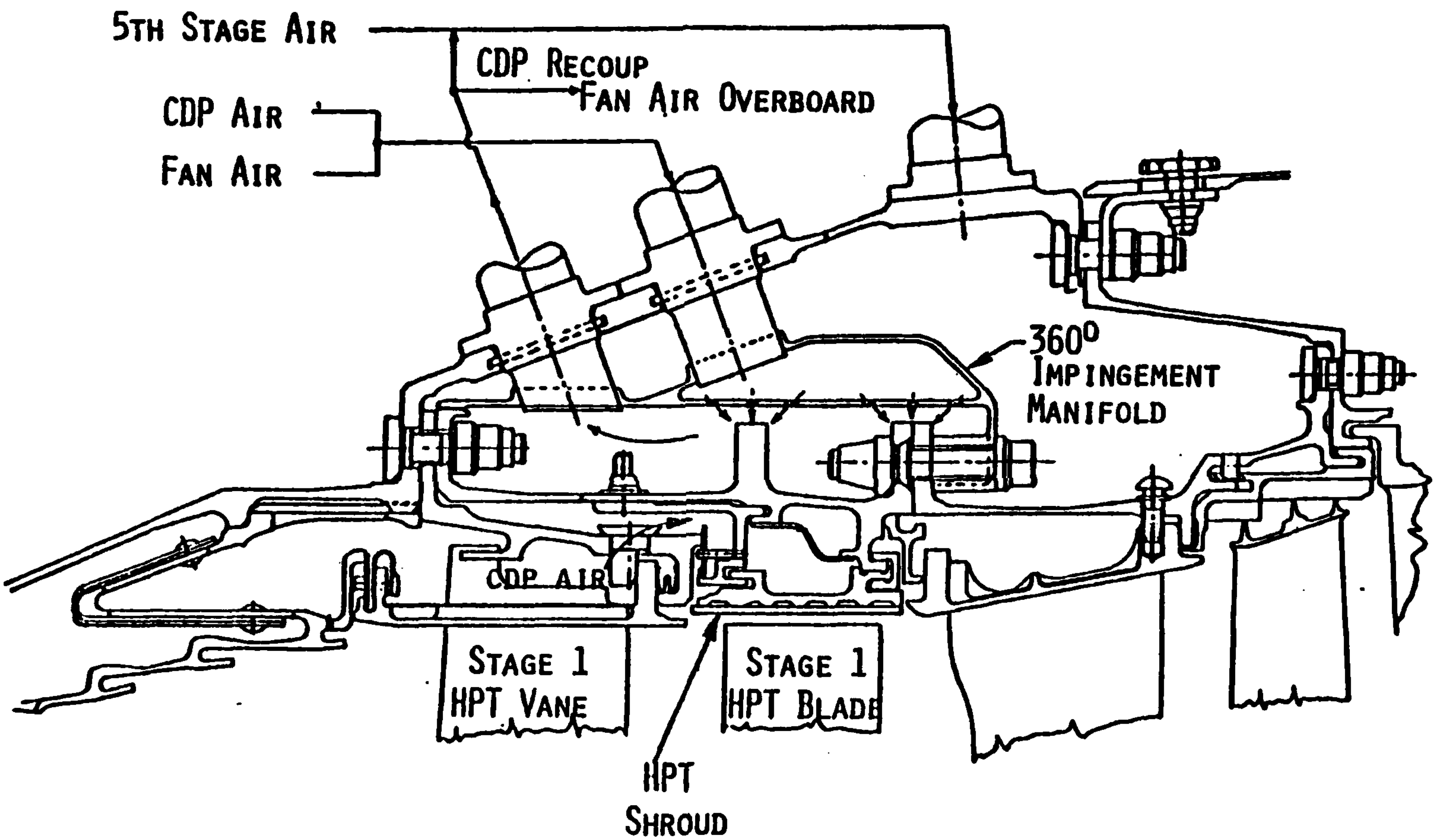


Figure 16. Thermal Turbine Active Tip Clearance Control System; Variable Air Source: Fan,CDP (Concept No. 6).

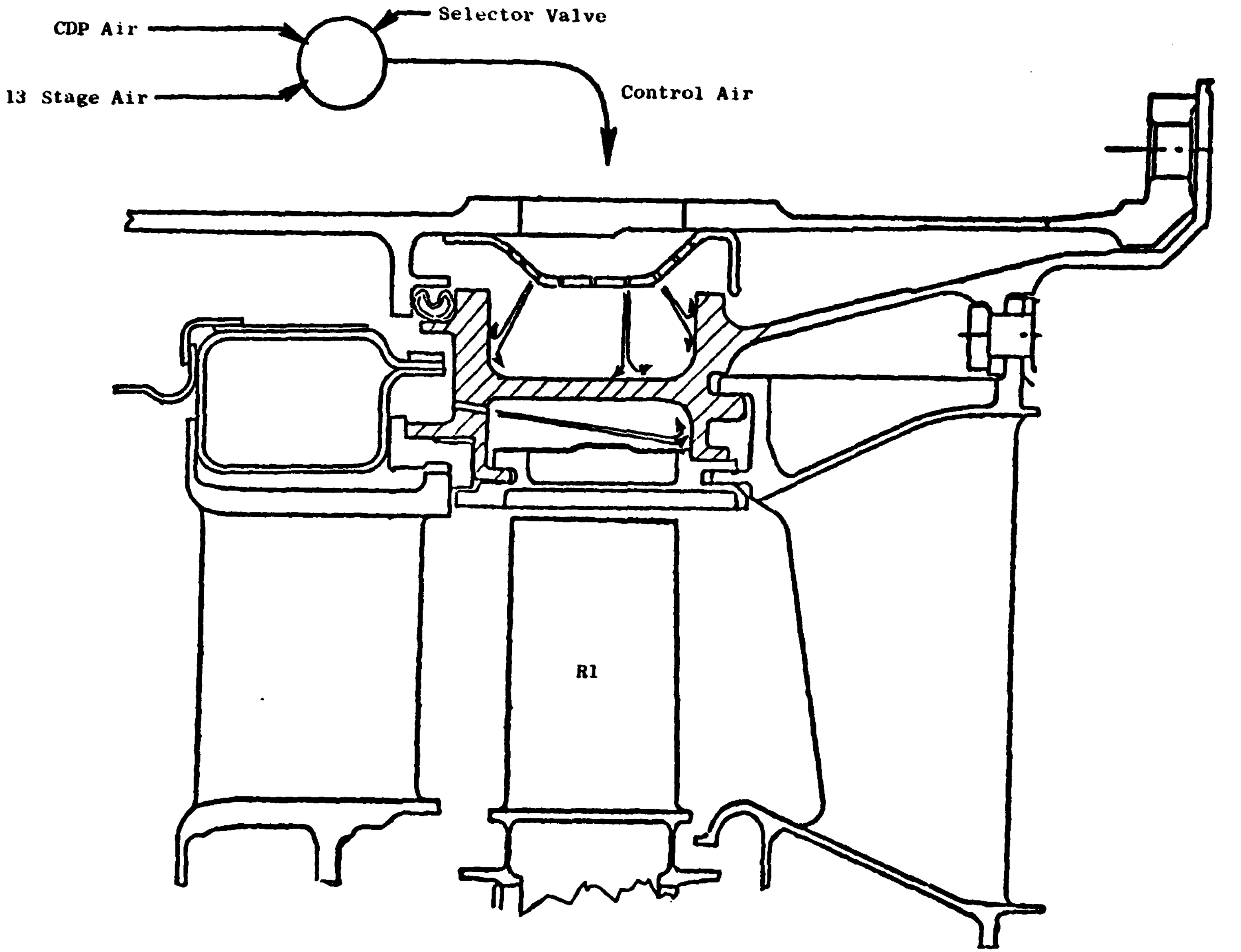


Figure 17. Thermal Turbine Active Tip Clearance Control System, 13th Stage and CDP, Concept Number 7.

3.1.7 Thermal System/Fan Air

The use of fan air only in an external impingement type system is shown in Figure 18 for Concept No. 8. The approach shown utilizes passive heating of internal hot CDP and 13th Stage air for driving the shroud supports outward and then applies fan cooling air externally to actively cool, driving the shroud supports inward. This system offers several major advantages. The use of fan air gives a large ΔT for large clearance change capacity, yet is a very insensitive loss to cycle performance. The concept is fail safe in that the loss of cooling flow results in opened up clearances and no tip rubs at high power settings. Simplicity is evident in that no airframe interface is required and the external ACC components are easily maintained. The relatively small penalties of the system are the slow response time with cooling air off, due to the massive rings of the shroud support.

3.1.8 Concept Selection for Further Study

In order to carry out further evaluation of concepts in specific engine applications, the proceeding concepts were reviewed and the most attractive ones selected.

The relative advantages and disadvantages of each concept were judged with emphasis on simplicity and least performance penalty. Simplicity was a major factor since this was an indicator of both weight and cost penalties that would be charged. Least performance penalty was jointly considered since this would directly offset any clearance/performance gains.

This approach found the electrical heating concepts to be unattractive in their complexity and risk of system malfunction rubs. The mechanical actuation systems also were complex in their large number of cams with large uncertainties in roundness control and stress/life. The heat exchanger (HEX) supplemented air system required a heavy, costly HEX to achieve small improvements in ΔT.

The most attractive/simple systems were the all air concepts. Of these the ones using the lowest pressure supply air or lowest supply-to-dump ΔP were the most efficient from a cycle standpoint. Thus, the fan air cooling concept was selected as the overall ACC system to be studied. This basic system was then specifically tailored to the characteristics of each engine.

For the CF6 two-stage turbine, the Thermal System/Fan Air System (Figure 18) was chosen with several variations on the basic idea. The construction would be a single-wall casing incorporating rings at the shroud support points. The air routing would be of four types: with or without internal passive CDP heating and with or without external active fan air cooling.

A single concept was chosen for both the CFM56 and F101 turbines because of the considerable similarity in their basic configurations. The ACC concept to be applied to them was to utilize the ring-supported shrouds and the double-wall casing (Concepts 5 and 6 in Figures 15 and 16). The several air

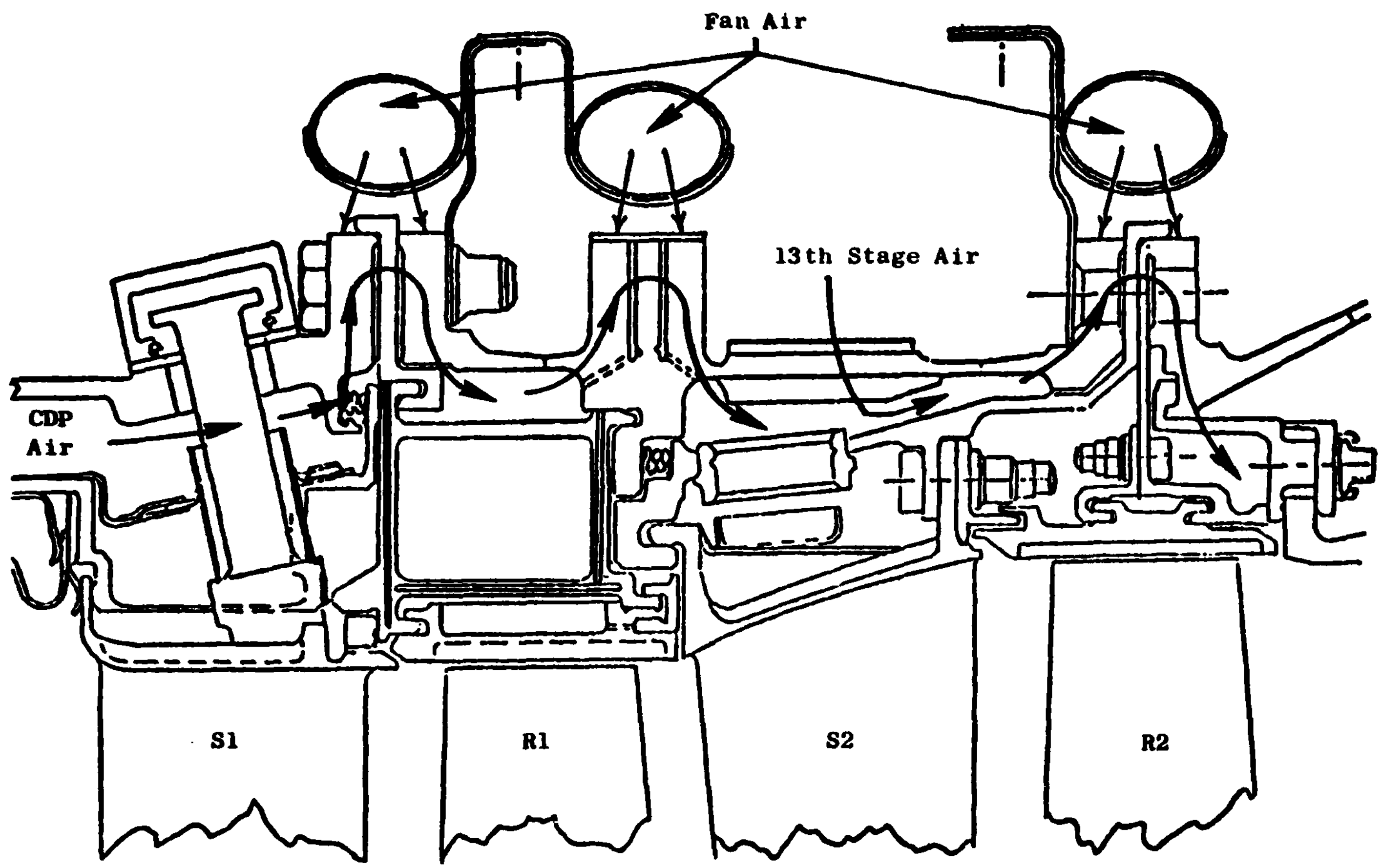


Figure 18. Thermal Turbine Active Clearance Control System Fan Air Impingement, Concept Number 8.

routing techniques to be studied were continuous internal passive heating combined with external active air from CDP heating, 5th stage air heating or fan air cooling.

3.2 CFM56/F101

3.2.1 Heat Transfer Design and Analysis

3.2.1.1 Conceptual Studies and Design Selection

To provide a base for improved clearance designs, current engine high pressure turbine clearance systems were reviewed in detail. Both production and growth-version F101 and CFM56 engines were studied and results are summarized in the following:

F101/PV	Passive clearance control with internal 5th and CDP air as thermal control media.
CFM56	Active clearance control with internal 5th and 9th stage air as thermal control media.

Figure 19 shows the present F101/PV engine HPT passive clearance control system. CDP air is used to cool the 1st stage turbine shroud, and the 5th stage bleed air is used to cool the 2nd stage vane after flowing over the HPT casing and support structures. The 1st stage shroud support and structural arrangement are IN903 alloy, which is the current clearance control system on the F101. The passive clearance control system has been designed to take advantage of the low thermal expansion coefficient of INCO 903.

Conceptual heat transfer designs to improve the current F101 clearance control are shown in Figures 20 and 21. Conceptual design No. 5, as shown in Figure 20, uses the CDP air for cooling the 1st stage shroud. The air is brought through a heat exchanger mounted in the cavity located above the combustor casing. It is then fed to a manifold in the vicinity of the outer casing flange support. Local tubes are attached to the flange wall at the locations of some of the flange bolt holes. The existing shroud support forward flange is reworked to allow the CDP air to enter the cavity between the shroud support and the nozzle outer support. The pressure in the cavity can be designed to be compatible with the present system. Since a considerable pressure drop has taken place in the present design to reduce leakage through the leaf seals, then the heat exchanger, the holes in the flange, and the piping losses can be sized as a system to match the desired pressure drop of the existing F101X engine system. The air is then routed to the shroud cavity through holes similar to the present engine cooling airflow system. Fifth stage bleed air fed from a manifold located in the compressor casing is used to cool the 1st stage shroud support structure and the 1st stage low pressure (LP) turbine nozzle diaphragm.

The 5th stage air piping is split to provide a parallel passageway for this design concept. One route continuously feeds air to the LP turbine turbomachinery (as in the present design) and the other passage directs the

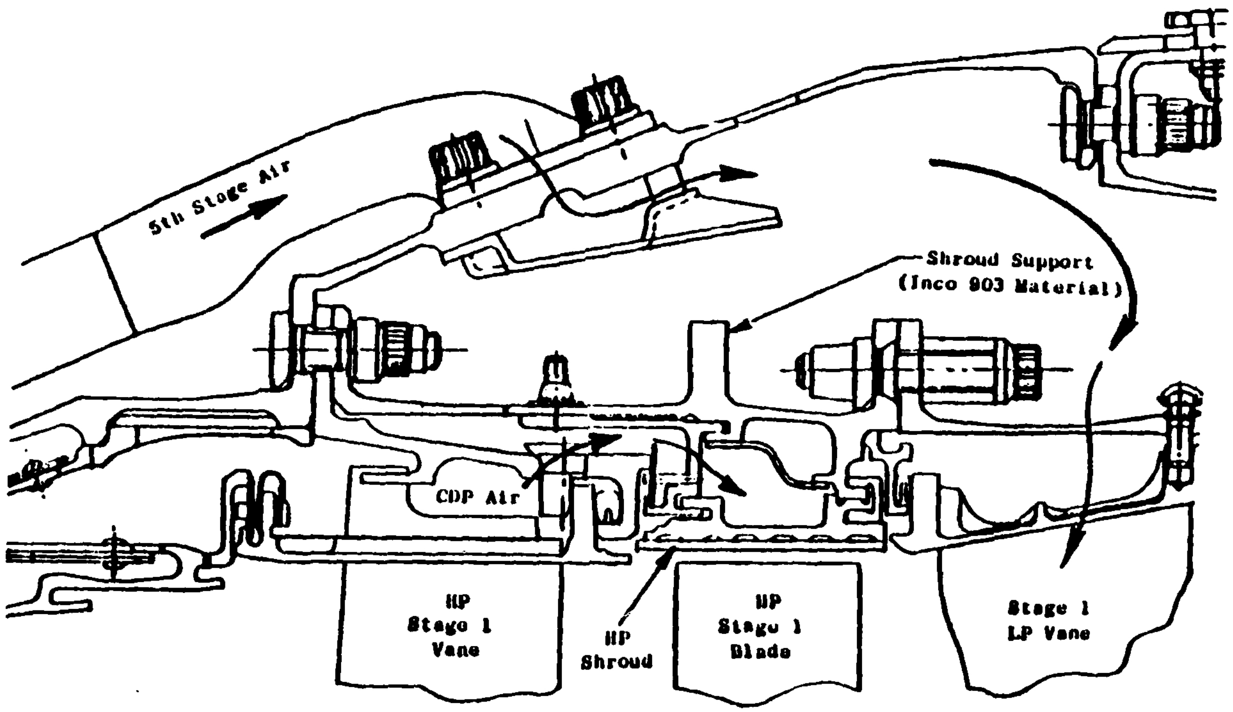


Figure 19. Present F101 High Pressure Turbine Shroud Tip Clearance Control System.

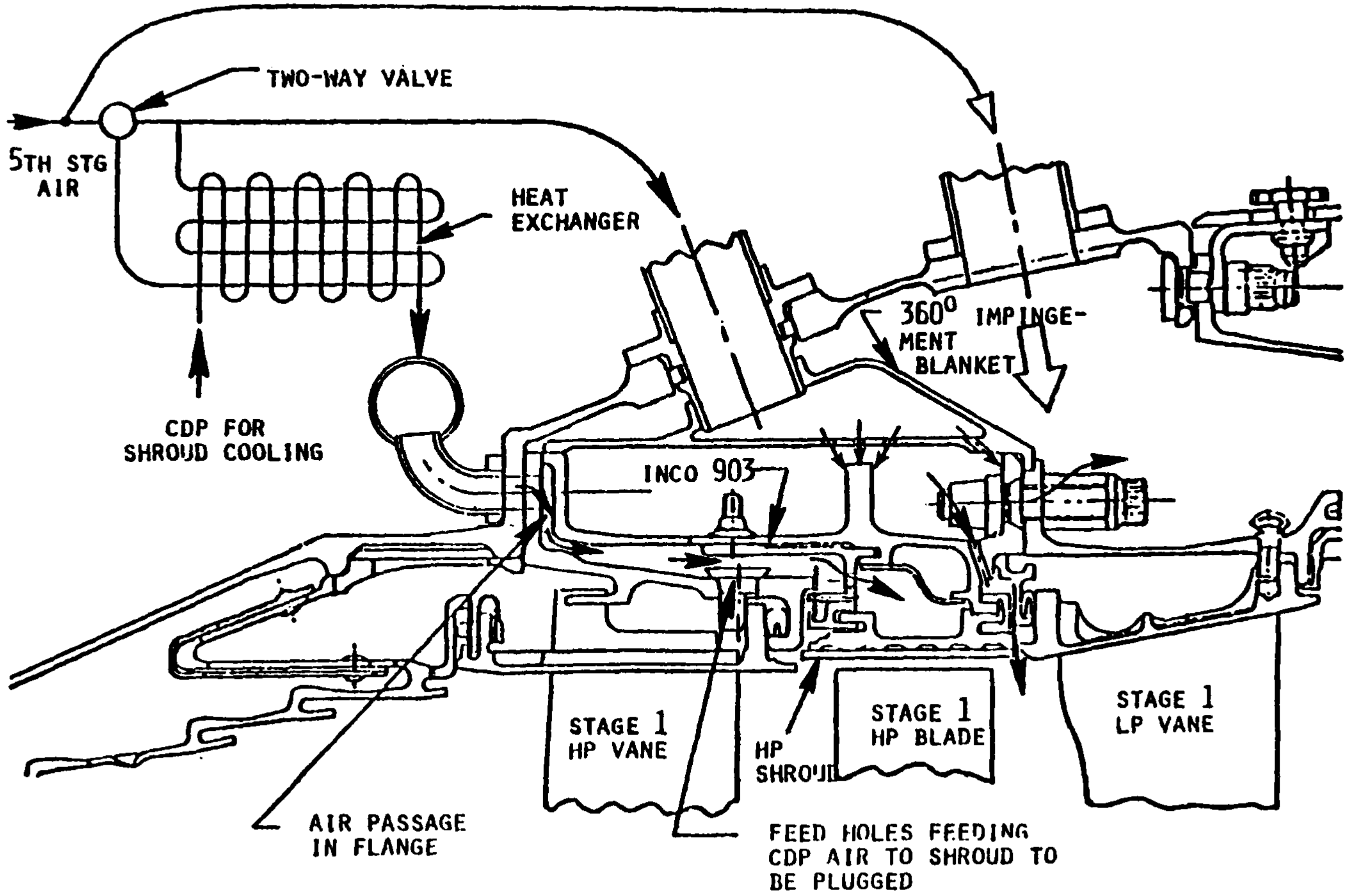


Figure 20. High Pressure Turbine Thermal Active Tip Clearance Control System, Concept Number 5.

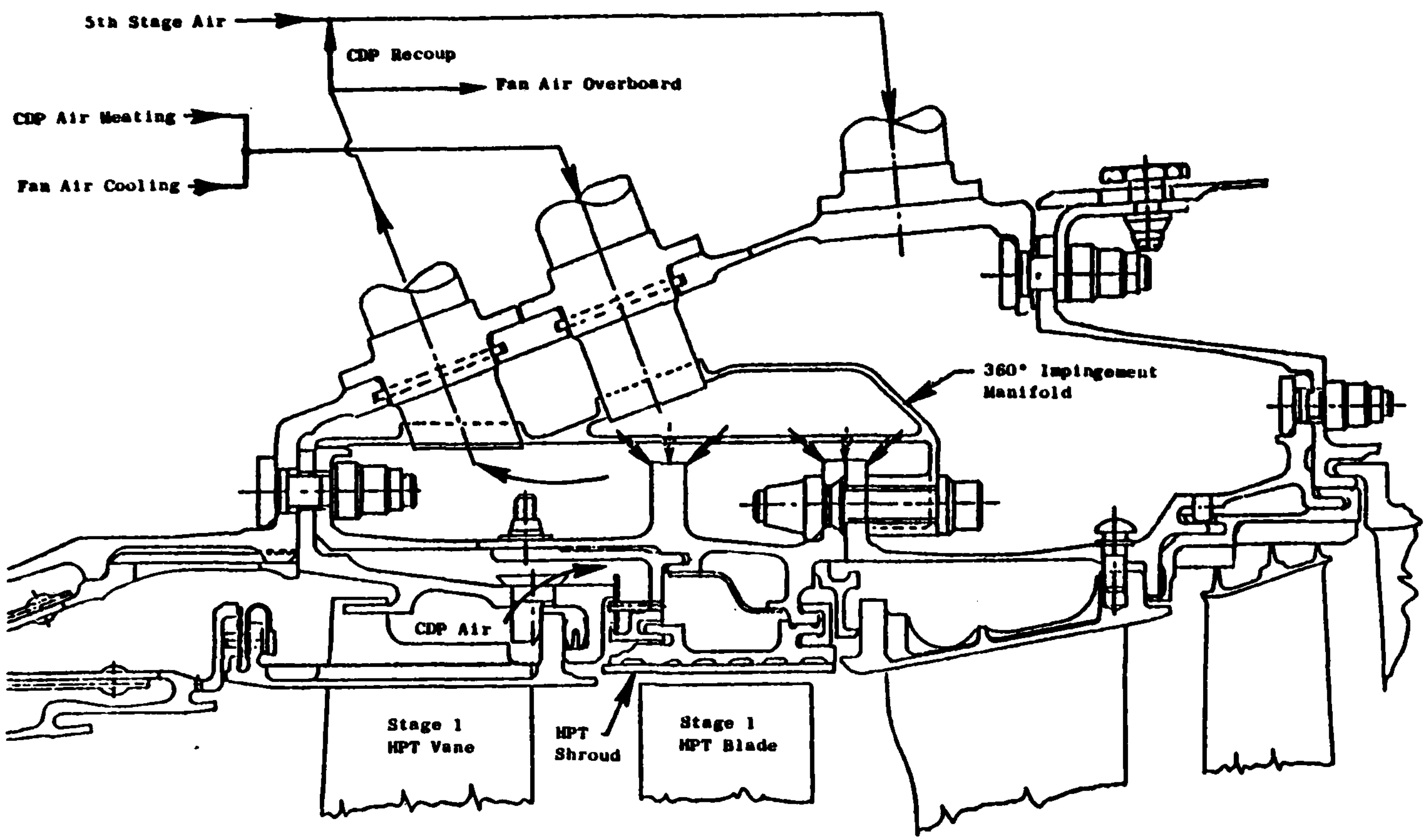


Figure 21. High Pressure Turbine Thermal Active Tip Clearance Control System, Concept No. 6.

flow through a two-way valve in a parallel circuit. One leg of the parallel circuit goes to a heat exchanger where it picks up heat from the CDP air going to the shroud. The other leg in the two-way system supplies unheated 5th stage air.

The purpose of the two-way valve system is to activate a closure of one side of the parallel circuit and to allow airflow through the other. The automatic sequencing of the valve to match the clearance control needs will determine whether the 5th stage air will be routed through the heat exchanger or bypass it to provide the thermal response for the shroud support structure.

If the requirement is for heating the air to provide fast growth, as in the takeoff mode, the valve opens on the heat exchanger side and heats the 5th stage air from the CDP air. Since the CDP air is always passing through one side of the heat exchanger, the pipes are at the CDP air temperature and can instantaneously heat the 5th stage air. While the 5th stage air is being heated, the CDP temperatures drops until an equilibrium temperature is achieved. Using this cooler CDP air for the shroud provides a reduction in cooling temperature, resulting in low flow for an increase in turbine efficiency.

Even though detail efficiency values were not calculated, the trend toward lower flow and resulting higher efficiency identified the advantage of this conceptual system.

The second conceptual design (Concept No. 6) at stage shroud support modulates coolant flow to match the stator growth to that of the turbine growth (see Figure 21). This system is similar to Concept No. 5, but utilizes impingement of fan and CDP air to control shroud growth. Hot CDP air is impinged to move the shroud out during short-time engine transients. Relatively inexpensive, cool, fan bypass air is impinged to move the shroud in at cruise. The active clearance control system utilizes two valves to control the cooling circuits. The first valve selects either CDP or fan bypass air to impinge on the shroud support structures depending on required shroud positioning. The second valve is actuated simultaneously with the first valve, to select the discharge flow path. When CDP air is used, the spent air exists through the 5th stage air piping and re-enters the casing over the LP turbine system. When fan bypass air is used, the spent fan air exits through the 5th stage air piping and is exhausted overboard.

Both conceptual designs are feasible to meet the F101/CFM56 engine active turbine clearance control requirement. However for Concept No. 5, an effective, inexpensive and lightweight heat exchanger becomes a prerequisite for the active control system. For these reasons, Concept No. 6, as described in Figure 21, was selected for final design analysis.

3.2.1.2 Heat Transfer Analysis

The CFM56/F101 high pressure active turbine clearance control heat transfer design for Concept No. 6 is given in Figure 22. The design conditions for selected engine missions are listed in the following:

Air Source	Nominal Flow Initial Selection	T_{Air} - °F (Takeoff) CFM56 Comm/AWACS	Mixed F101
CDP	0.411% W_{25}	1080	1055
Fan	0.150% W_{fan}	167	260
Fifth Stage	0.750% W_{25}	740	745

The flow values shown are the initial selections which, for CDP and 5th stage are the present CFM56 quantative and for fan air was a quantity shown effective in parametric work from earlier impingement ring studies. As illustrated in Figure 22, the heating and/or cooling of the turbine 1st stage shroud support structure and casing is accomplished by impinging the CDP air (for heating) and/or the fan air (for cooling) on the two structural rings that govern the thermal growth of the stator . Each ring has three rows of impinging air jets from 200 evenly spaced 0.045 inch diameter holes in each row. The CDP/fan air feed and exit pipes have 1.4 inch inside diameters. There are two feed and two exit pipes spaced 180° apart.

The objective of heat transfer analysis was to predict the detail metal temperature distributions in the turbine 1st stage shroud support stucture and casing so that the mechanical analysis would yield the thermal growth of these structures and hence determine the turbine 1st stage tip clearance, given the rotor growth signature. The engine missions, selected from system pay-off studies for the heat transfer analysis, are given in Figure 23.

The General Electric Transient Heat Transfer Program, Version D (THTD) was used to calculate the temperature distributions. A nodal breakdown of the casing and the support structures is shown in Figure 24. The THTD computer program calculates the transient temperatures at the centroid of each node. Then applicable thermal boundary conditions are specified for all of the node. Typical transient boundary air temperatures for the selected F101 mission are presented in Figure 25. Typical calculated average transient temperature for the forward support ring is shown in Figure 26 for the CFM56 Commercial Mission as defined in Figure 23.

Hot rotor reburst analyses, which started at the end of the first climb leg, were conducted at the following times: +40 seconds, +160 seconds, and +320 seconds. Typical hot rotor reburst results for the ring's average temperature response are given in Figures 27 and 28 for the selected CFM56 Commercial Mission using CDP heating, fan air cooling, and no heat/no cool conditions.

Table 8 lists all basic cases for which a complete thermal analysis was run and for which metal temperature distributions are available for tip clearance calculations.

Two additional thermal analyses were made for the case 4 CFM56 Commercial Mission by varying the fan airflow rate from the base design value of 0.15% W_{fan} to 0.05% W_{fan} and to 0.01% W_{fan}.

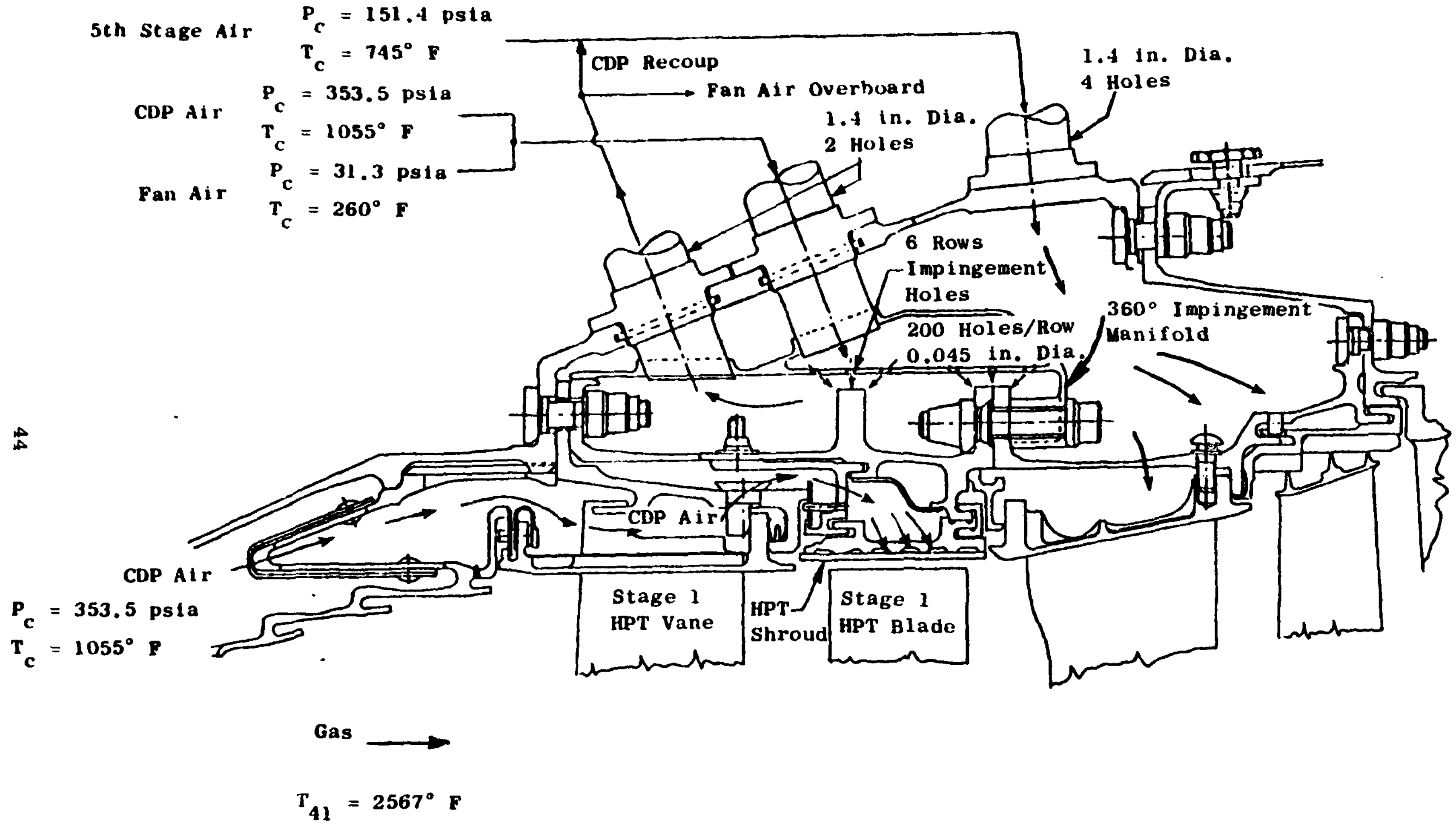


Figure 22. Cooling/Heating System Definition for Modified F101/CFM56 High Pressure Turbine Thermal Active Clearance Control System.

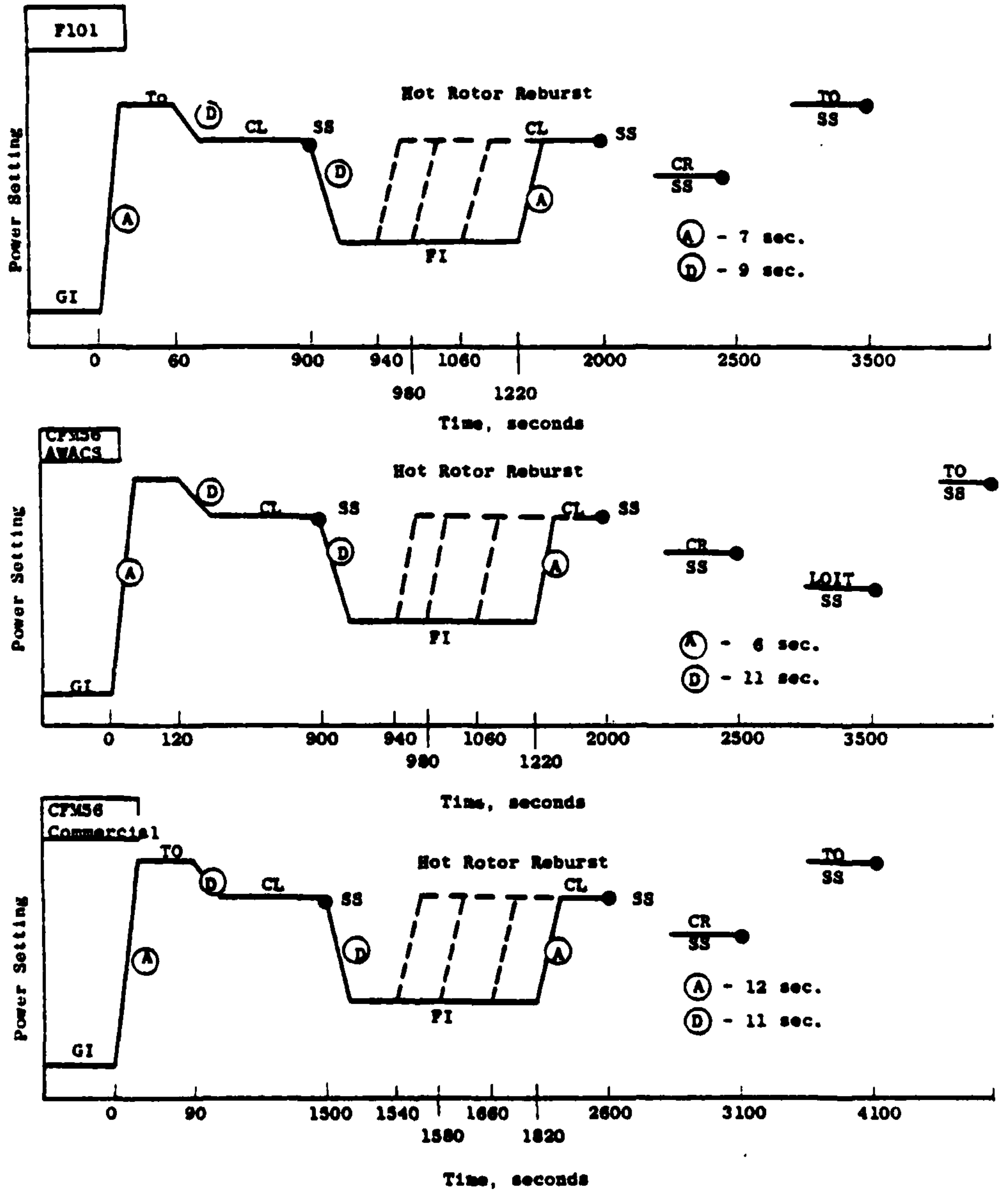


Figure 23. F101/CFM56 Mission Definition for Thermal Analysis.

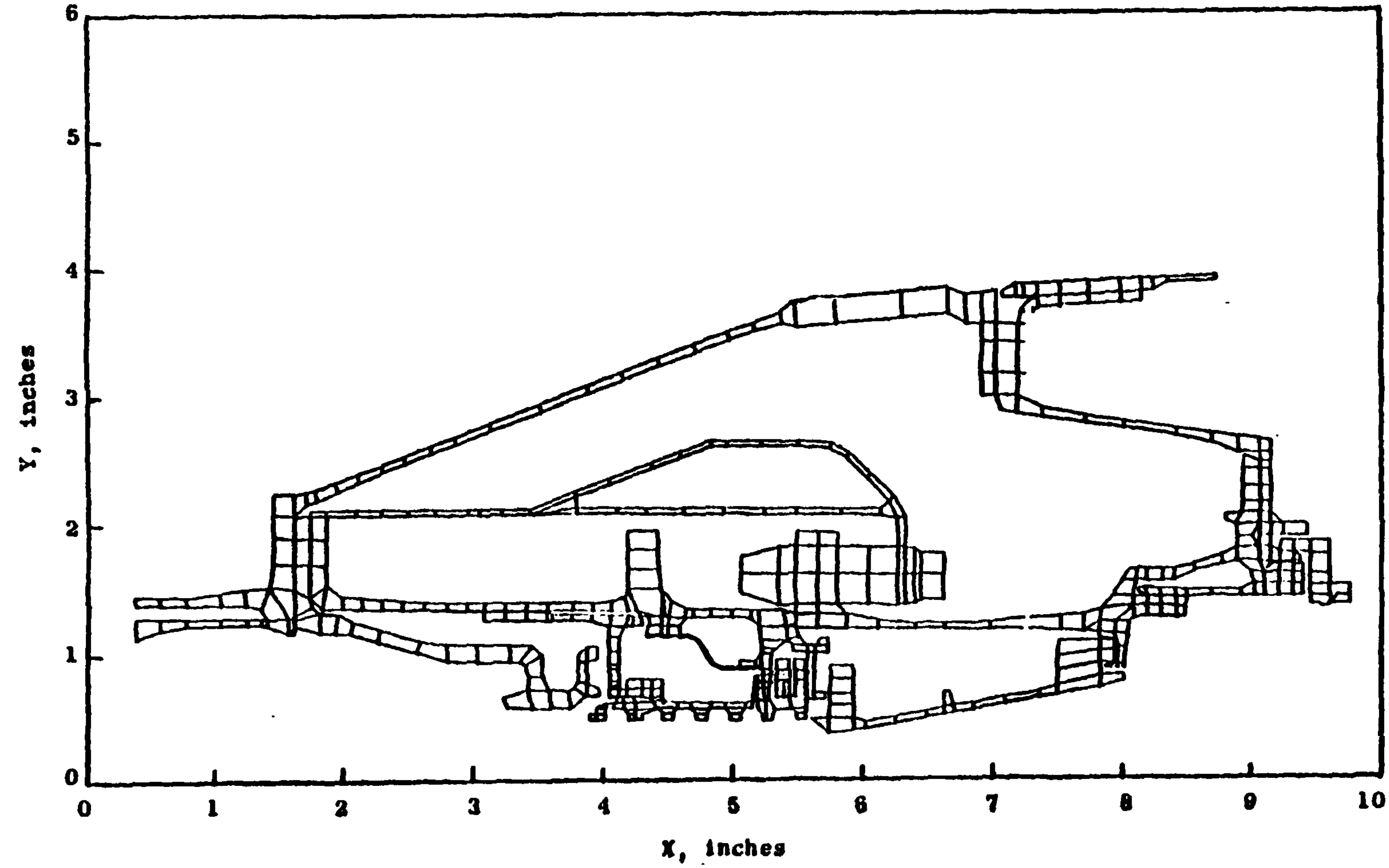


Figure 24. Heat Transfer Analysis Nodal Diagram of the CFM56/F101 High Pressure Turbine.

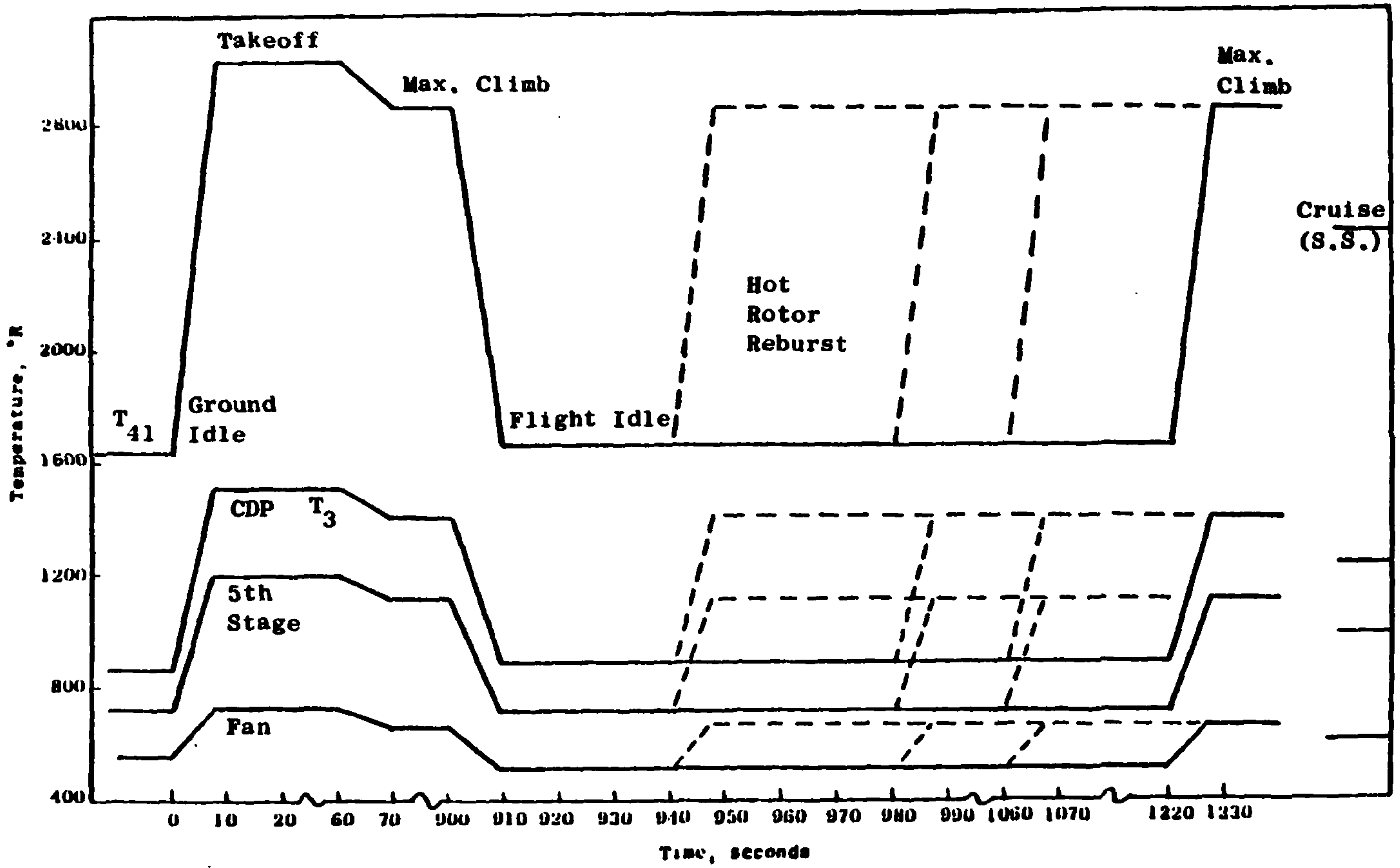


Figure 25. F101 Mission Cycle Thermal Transient Definition.

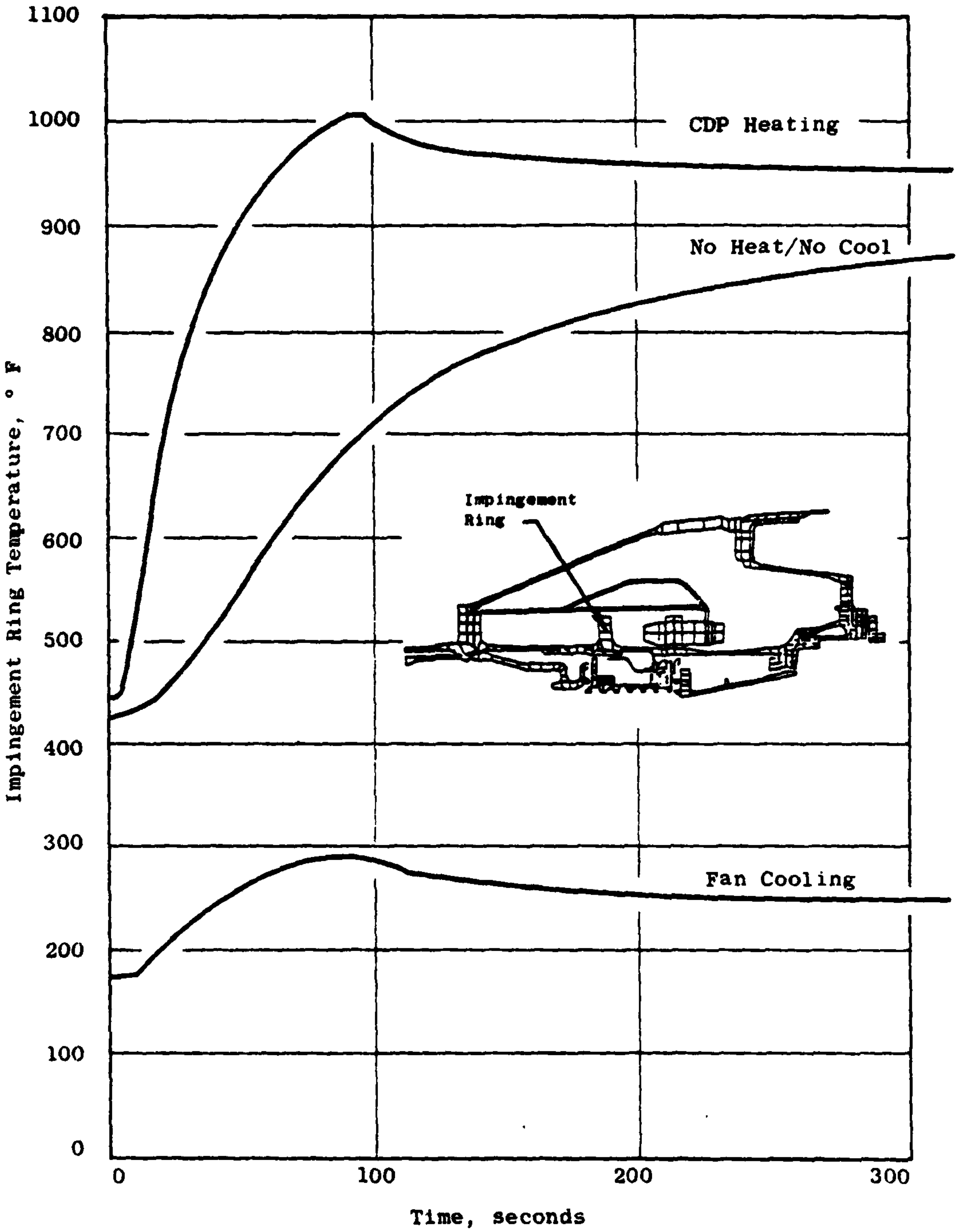


Figure 26. CFM56 Commercial Mission Takeoff.

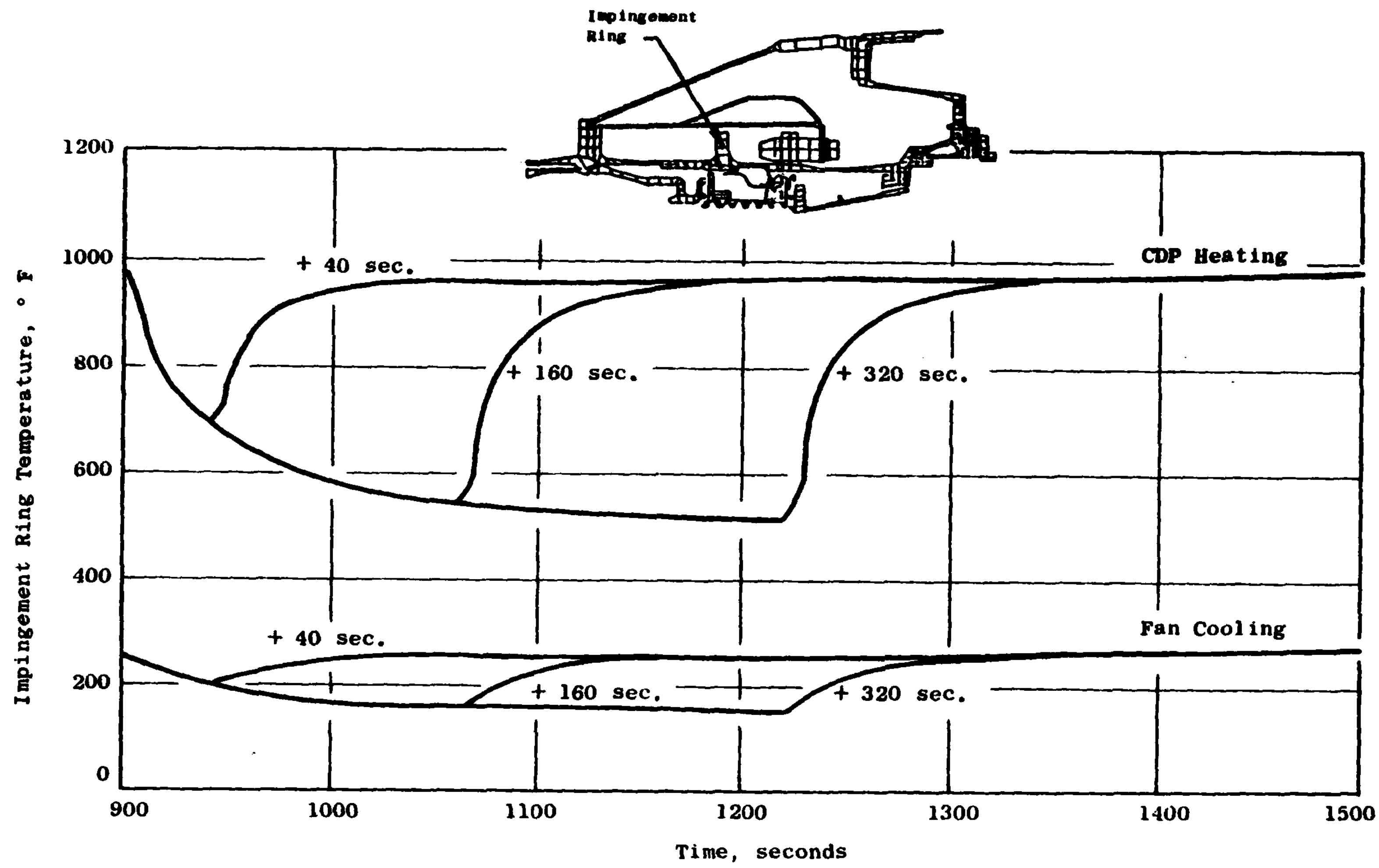


Figure 27. CFM56 Commercial Mission Hot Rotor Reburst CDP Heated or Fan Cooled Impingement Ring.

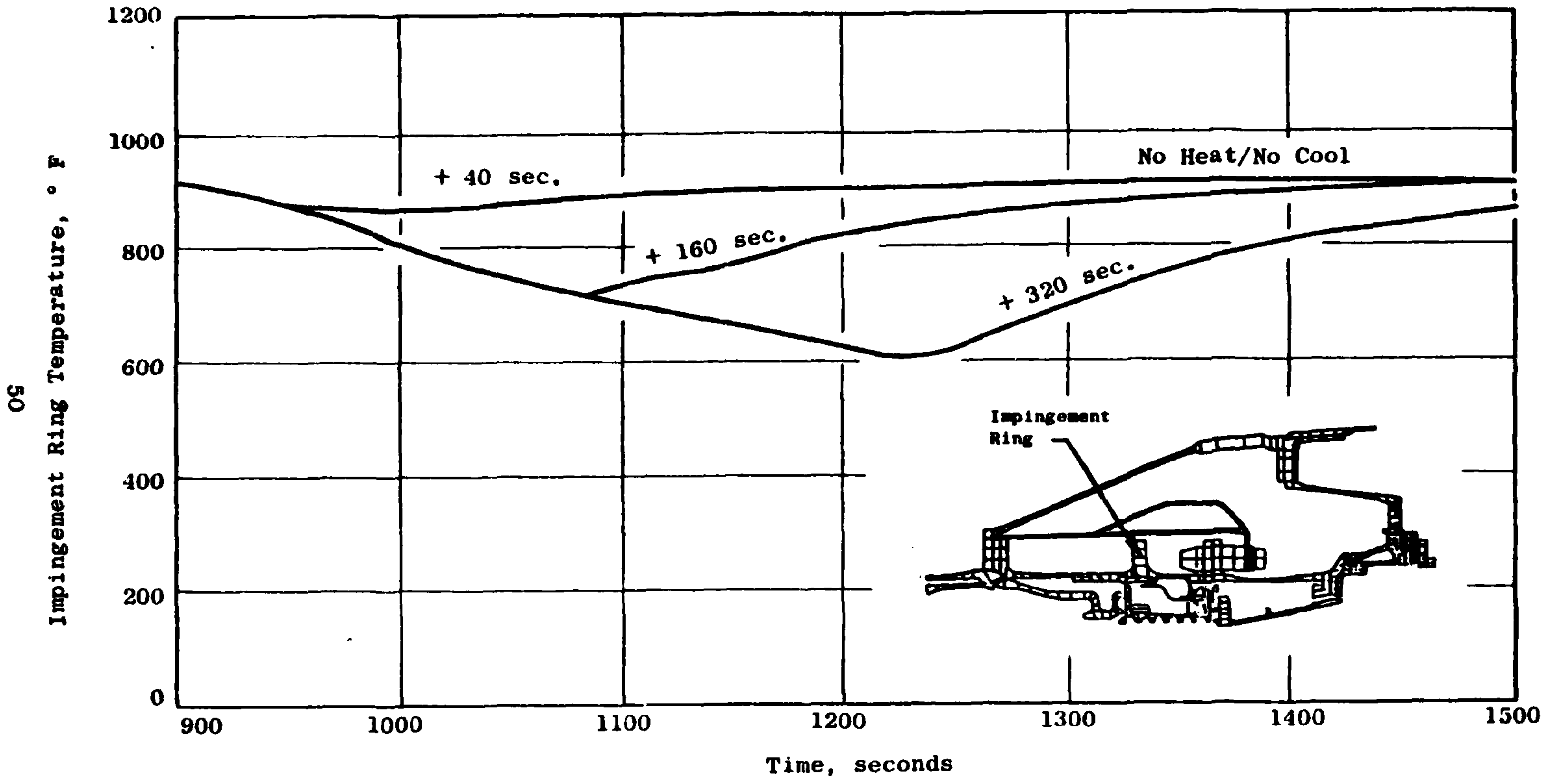


Figure 28. CFM56 Commercial Mission Impingement Ring Temperature at Hot Rotor Reburst: No Heat or Cooling.

Table 8. Summary of Thermal Analysis Cases CFM56/F101 Turbine Configuration.

Case		CFM56 Commercial (90 sec. T.O.)	CFM56 AWACS (120 sec. T.O.)	F101 Mixed (60 sec. T.O.)
Nominal Flow				
1. No Heat/No Cool		X	X	X
2. CDP Only (0.411% W_{25})		X	X	X
3. a) Fan Only (0.15% W_{fan})		X	X	X
b) Fan Only (0.05% W_{fan})		X	X	X
c) Fan Only (0.01% W_{fan})		X	X	X
4. Fifth Only (0.75% W_{25})		X	X	X
Hot Rotor Reburst (Nominal Flow)				
9. No Heat/No Cool	+40	X	X	X
	+160	X	X	X
10. CDP	+40	X	X	X
	+160	X	X	X
11. Fan Only	+40	X	X	X
	+160	X	X	X

3.2.2 Mechanical Design and Analysis

Determination of the basic rotor and stator radial growth characteristics was the initial step in designing and evaluating an ACC system for improved clearances. The rotor design can be modified to improve clearance but it has severe requirements of stress, life, and weight tht may conflict with ACC desires. For these reasons, a rotor redesign was viewed as beyond the scope of this program. Thus, stator modifications or tailoring would be the focal point of mechanical ACC design.

The current CFM56 and F101 rotors are very similar; their radial growth signature is shown in Figure 29. Stator growth signatures were than calculated for the various cooling approaches using temperature distribution from the nodal THTD results.

As discussed in Section 2, out-of-round factors are very significant in that they set the effective clearance limit that can be achieved in each system. Thus, even though an ACC concept can be devised which has the capability to achieve zero clearance, an out-of-round sealing circle could rub blade tips down leaving an elliptical gap. In this case, the full ACC closure would not be needed or even desired.

Each engine has its own unique out-of-round characterstics and, for this system clearance study, direct comparison of engines which included this characteristic could be misleading. For this reason, round engine evaluation was carried out and full ACC closure with the attendant full cooling/heating air quantity penalties were used.

Operating conditions used in these analyses were transients from ground idle through takeoff and climb, and chop-to-flight idle with a hot rotor reburst.

The transient engine mission growth characteristics are plotted first without using ACC and then with ACC.

The characteristics of clearance variation among the several operating modes were reviewed in order to identify which phases of operation required clearance adjustments. These adjustments are heavily influenced by material combinations as well as cycle temperatures and engine speeds.

As a general characteristic, at cruise the achievement of small clearance requires a stator decrease from the passive characteristic. By contrast, clearance during acceleration is governed by rapid rotor centrifugal growth. A limitation of current turbine systems is that they cannot provide matching casing growth during the first 10 to 15 seconds of acceleration.

The geometry of the CFM56/F101 stator section over the HPT blade was analyzed on GE's CLASS/MASS computer program. The computer nodal model of the stator geometry is shown in Figure 30.

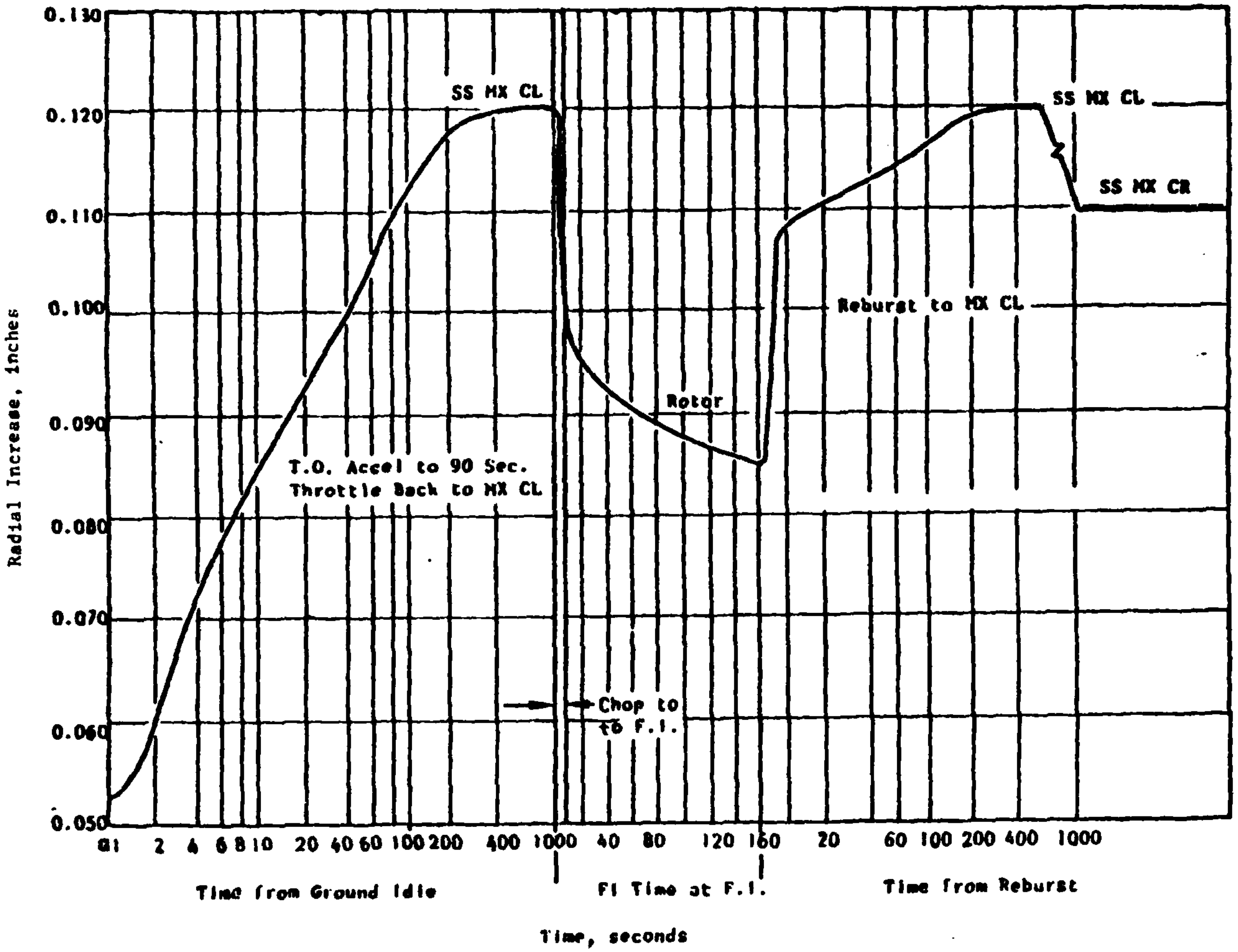


Figure 29. CFM56/F101 Rotor Signature.

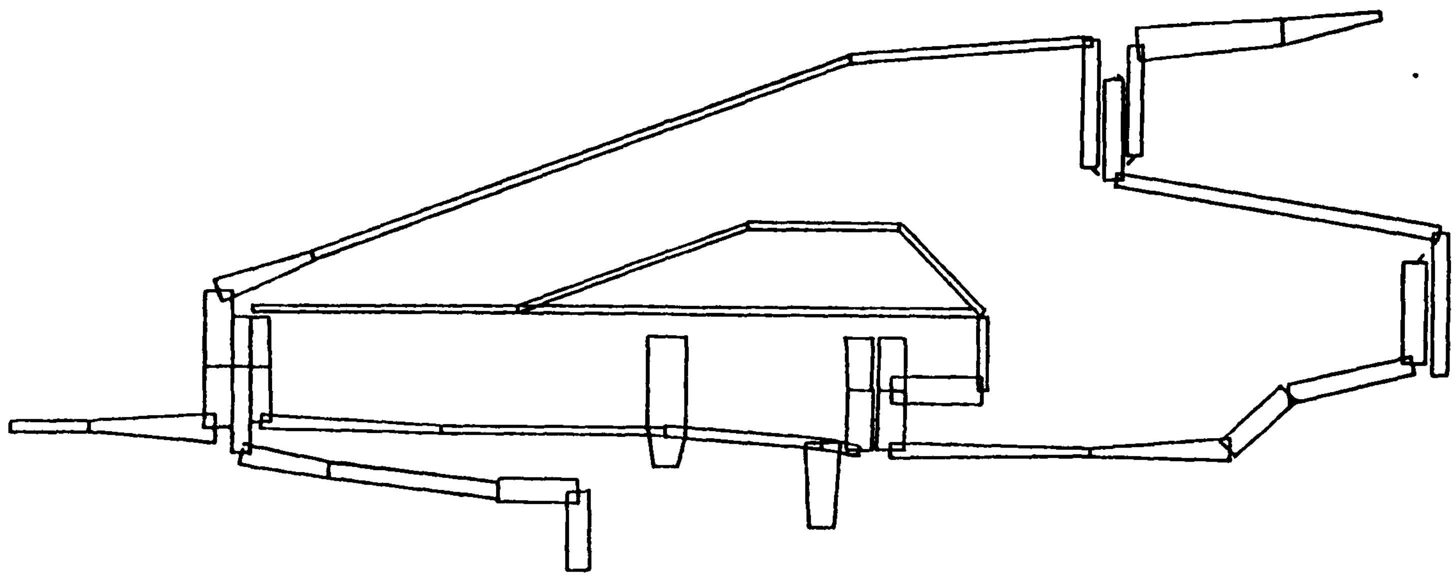


Figure 30. CLASS/MASS Model CFM56 and F101 HPT Case.

The engine response growths were calculated for the four stator cases of CDP air only, 5th stage bleed air only, fan air only, and no air as plotted in Figure 31. Then each of the basic hot stator cases (CDP, 5th, no air) was plotted individually against the rotor signature (see Figures 32, 33, and 34). The rotor/stator touch point was determined, then the resulting cold clearance and operating clearances evaluated.

Each figure was also plotted with one additional stator characteristic in order to compare the heating/cooling effects. In this phase of the analysis, out-of-round factors acting on the system were not considered.

In Figure 31, the "no air" system is set for minimum clearance at 20 seconds and gives 0.032 inch clearance at 1000 seconds and 0.025 clearance at cruise. The addition of fan air cooling can be seen to significantly reduce the clearance, in fact the full quantity of fan cooling (0.15% W_{25E}) can close beyond a "zero" gap clearance. This indicates the strength of the fan air concept and indicates the reserve capability which it offers.

Figures 32 and 33, show CDP with no air and 5th stage with no air, respectively. The major clearance values of each of these systems are shown in Table 9. These figures and the table provide the following conclusions:

- 5th stage advantages: with no supplemental air, has best clearances
- CDP: larger over shoot (clearance at 100 sec.)
- No air: least over shoot

  : larger clearance at 1000 sec and at cruise

When supplemental air is considered on each system the following results are found:

- No air: helps the CDP system at all points after 100 sec.

  : helps the 5th stage only at over shoot
- Fan air: helps all systems

  : offers considerable reserve closure capability

An understanding of the effect of no air can be seen from Figures 31 through 34. No air around the shroud support gives the support a starting idle diameter increase larger than with fan air or 5th stage, but slightly less than with CDP. During accel the support with no air is much more sluggish in radial growth response. This would cause the worst rotor rubs and so the shroud must be set with a large cold gap to avoid them. Once this gap is set, the stator is well matched to the rotor at the end of takeoff and small overshoot (extra clearance) is seen at the 100 second point. Similar sluggish decel response is seen in the no air support which means rotor shrinkage is quicker and larger decel/cruise clearances result. Adapting the no air

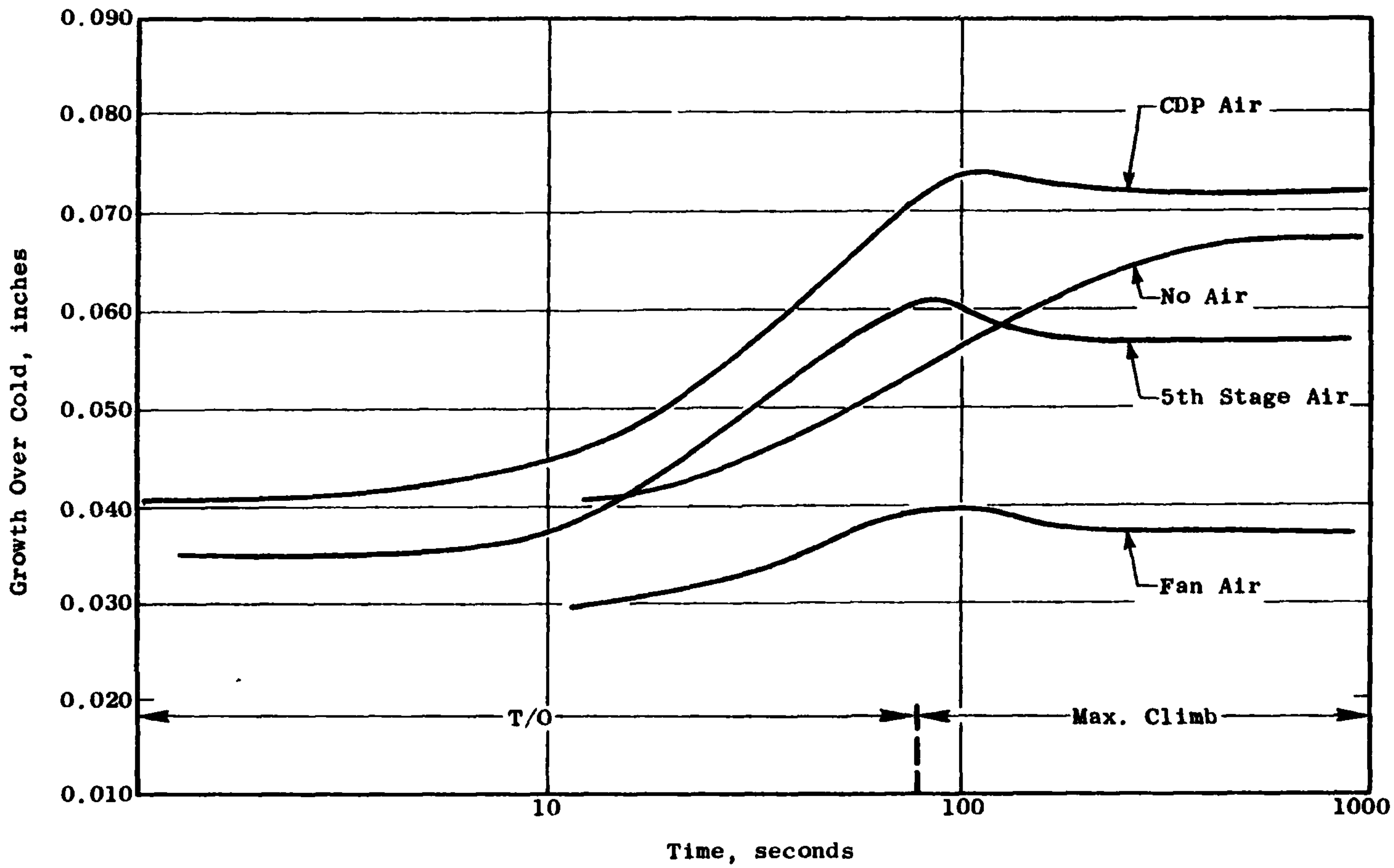


Figure 31. Cooling/Heating Effects on CFM56/F101 Stator Radial Growth.

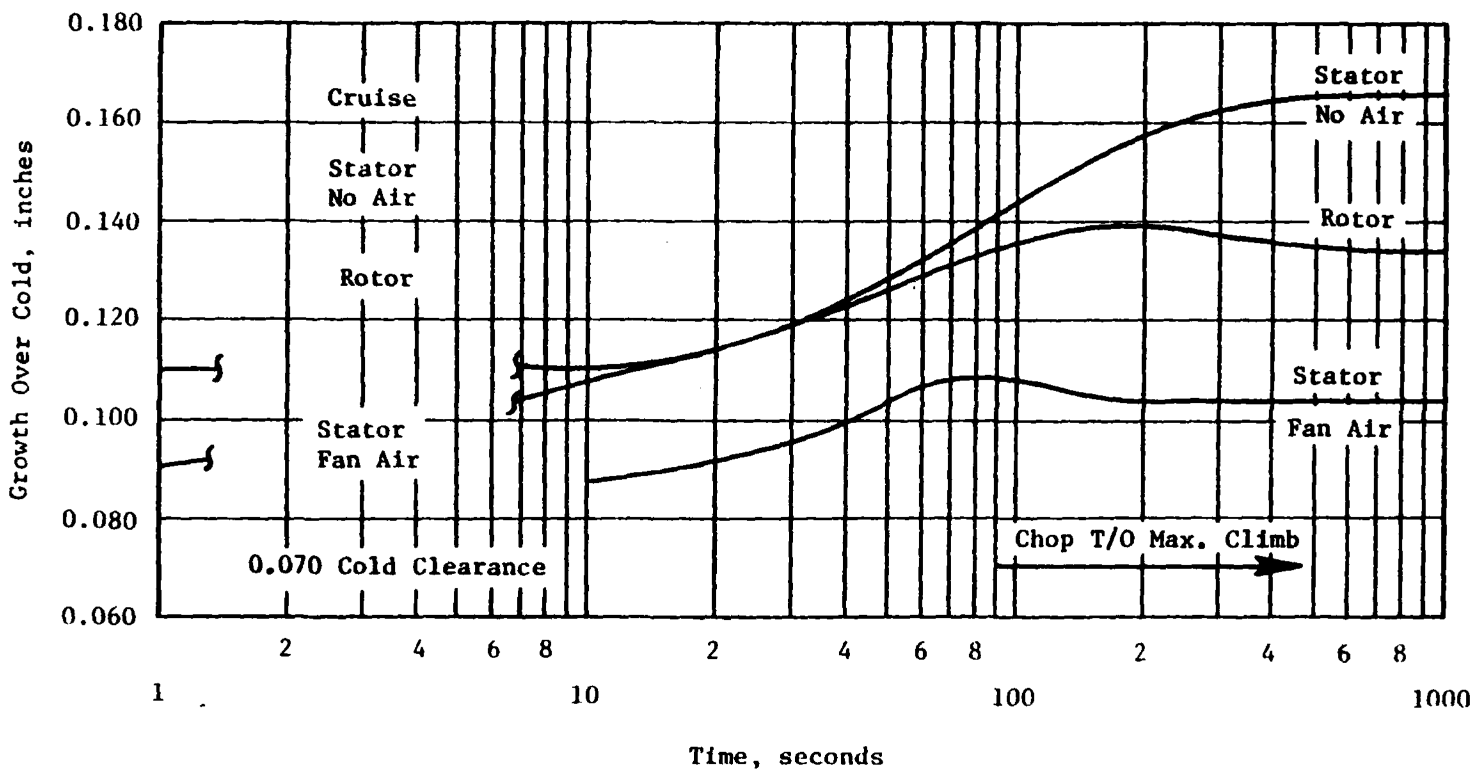


Figure 32. CFM56 Commercial Rotor-Stator Clearance ACCEL G/I - T/O - MxCL (No Air and Fan Cooling).

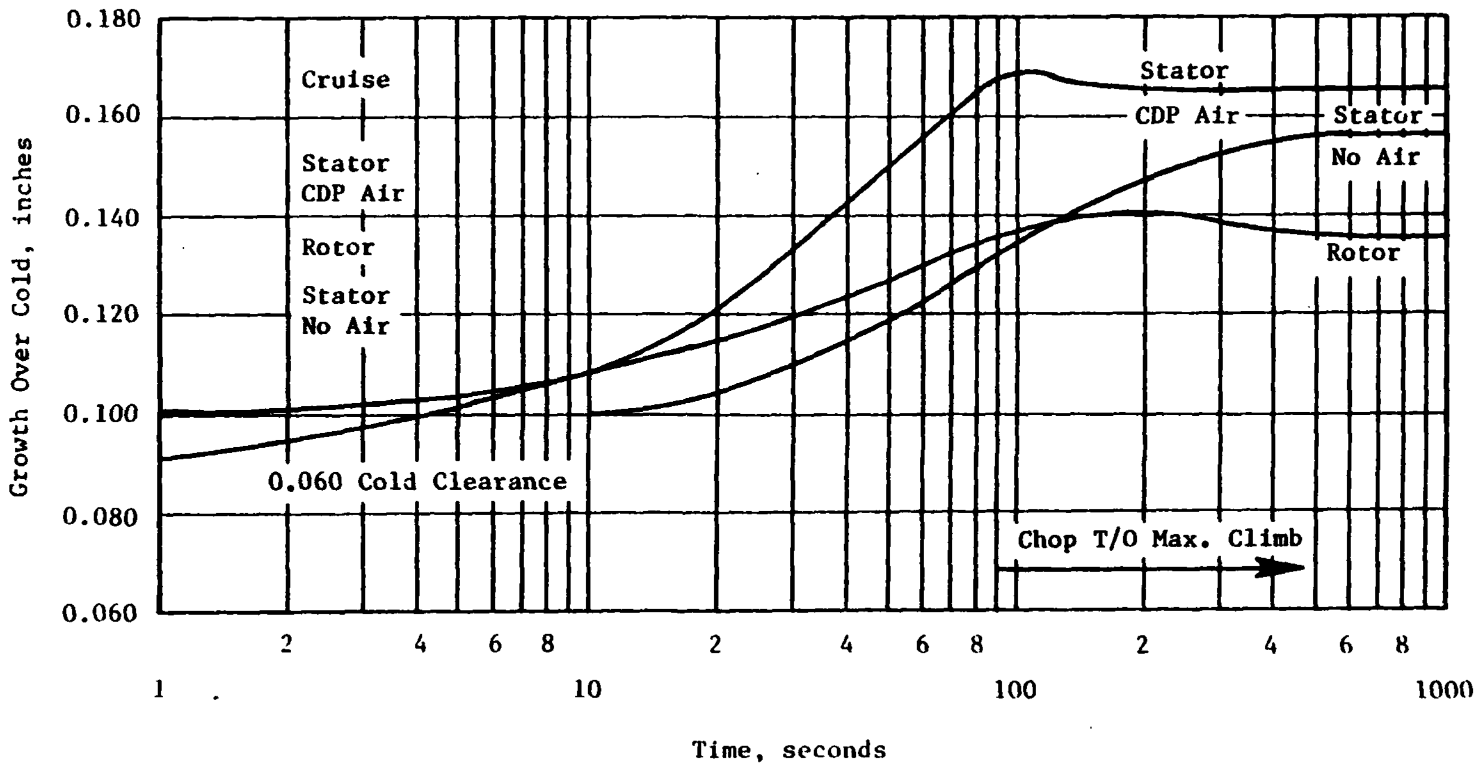


Figure 33. CFM56 Commercial Rotor-Stator Clearance ACCEL G/I - T/O - MxCL (CDP Heated and No Air).

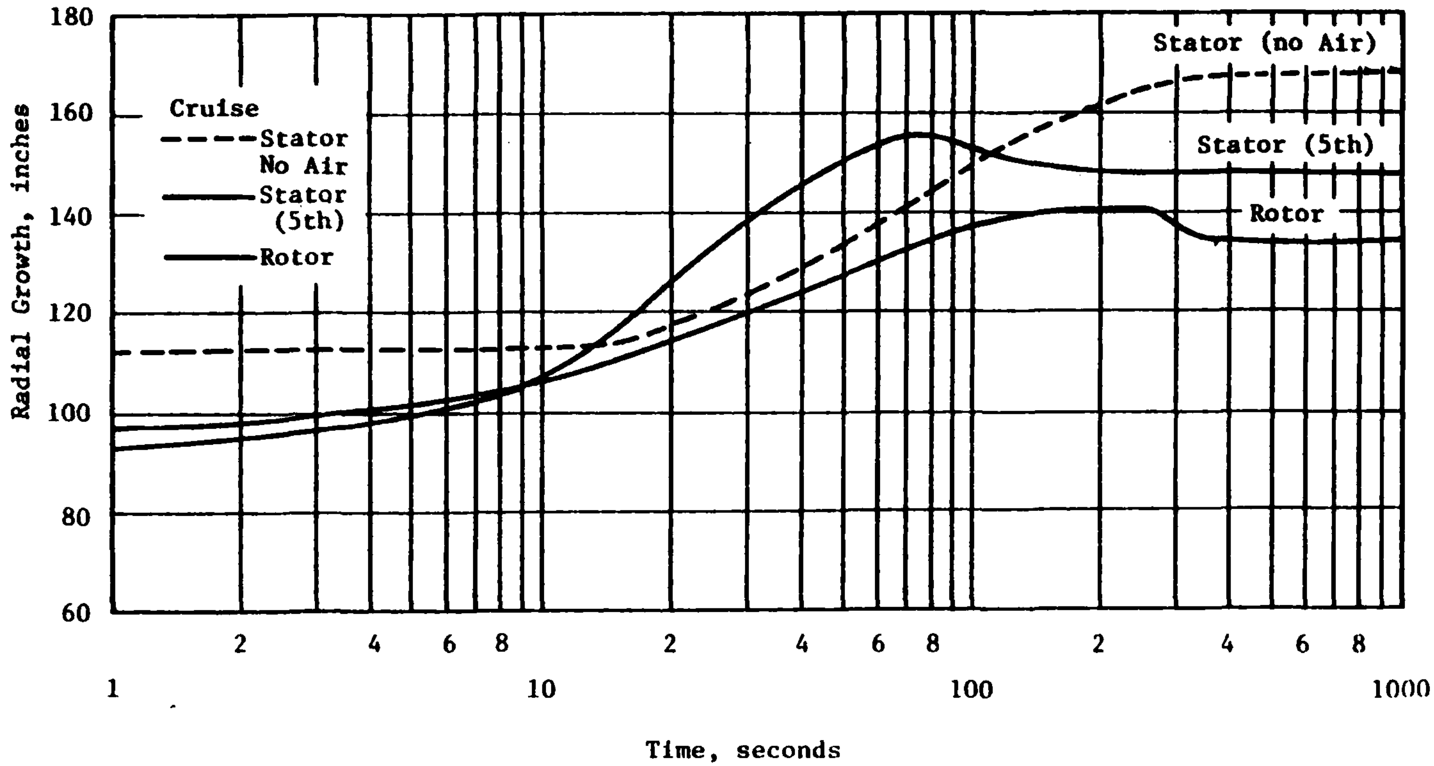


Figure 34. CFM56 Rotor-Stator Clearance ACCEL, GI - T/O - MxCL (5th Stage Air).

Table 9. CFM56/F101 Base Turbine Clearances.

System	Touch Point Time	Clearances (Inches)			
		Cold	100 sec	1000 sec	Cruise
No Air	20 sec	0.070	0.013	0.32	0.025
+Fan	---	0.070	-0.029	-0.030	-0.027
CDP	10 sec	0.060	0.032	0.030	0.022
+No Air	---	0.060	-0.002	0.021	0.014
+Fan	---	0.060	-0.044	-0.041	-0.038
5th	9 sec	0.072	0.019	0.024	0.008
+No Air	---	0.072	0.012	0.034	0.026
+Fan	---	0.072	-0.030	-0.032	-0.026

characteristics at selected time points to the CDP air system could be done by turning off the CDP and gaining a desirable damping effect on CDP overshoot tendencies.

As a result of these comparisons, the system chosen for final payoff evaluation was the 5th stage system supplemented with fan air. Since the 0.15% W_{25} fan air had shown more than enough closure capacity, further fine tuning was done by reducing the quantity of fan air to use only that required for closure to zero cruise clearance. It was found that ony 0.01% W_{25} fan was required. The stator/rotor clearance signature for this sytem is shown in Figure 35.

3.2.3 <u>Control System</u>

3.2.3.1 <u>Phase II - System Identification</u>

Phase II of the control study was to select the most promising system for each engine application. A preliminary evaluation was conducted prior to the completion of the heat transfer studies. In this preliminary proposal, clearance control air is controlled by two-way, modulating butterfly valves, actuated by fuel and controlled by an electro-hydraulic servovalve operated by a signal from the digital control. An electrical position transducer is included in each valve package to supply feedback to the digital control.

The compressor and LP turbine which require cooling air only, will be controlled by a single valve. The HP turbine, which requires both heating and cooling air, will be controlled by two independent valves. These systems are shown in Figure 36.

In working toward a preliminary design concept for controlling the clearance control air valves, the following alternatives were considered:

1. On-off function

2. Valves scheduled with rpm and operating condition with compensation for thermal lags

3. Calculation of clearance using thermal/mechanical equations and modulation of control valves to maintian desired clearance schedule

4. Measure clearance and modulate valves to maintain desired clearance schedule.

Alternative 4 is obviously an operationally desirable approach, but, as reported earlier, this system requires further refinement before being used on flight-type engines. Therefore, the preliminary design effort was limited to the other three alternatives. Alternative 3 was selected here because it offers the greatest flexibility. In selecting alternative 3, it was assumed that a digital control would be a part of the overall control system.

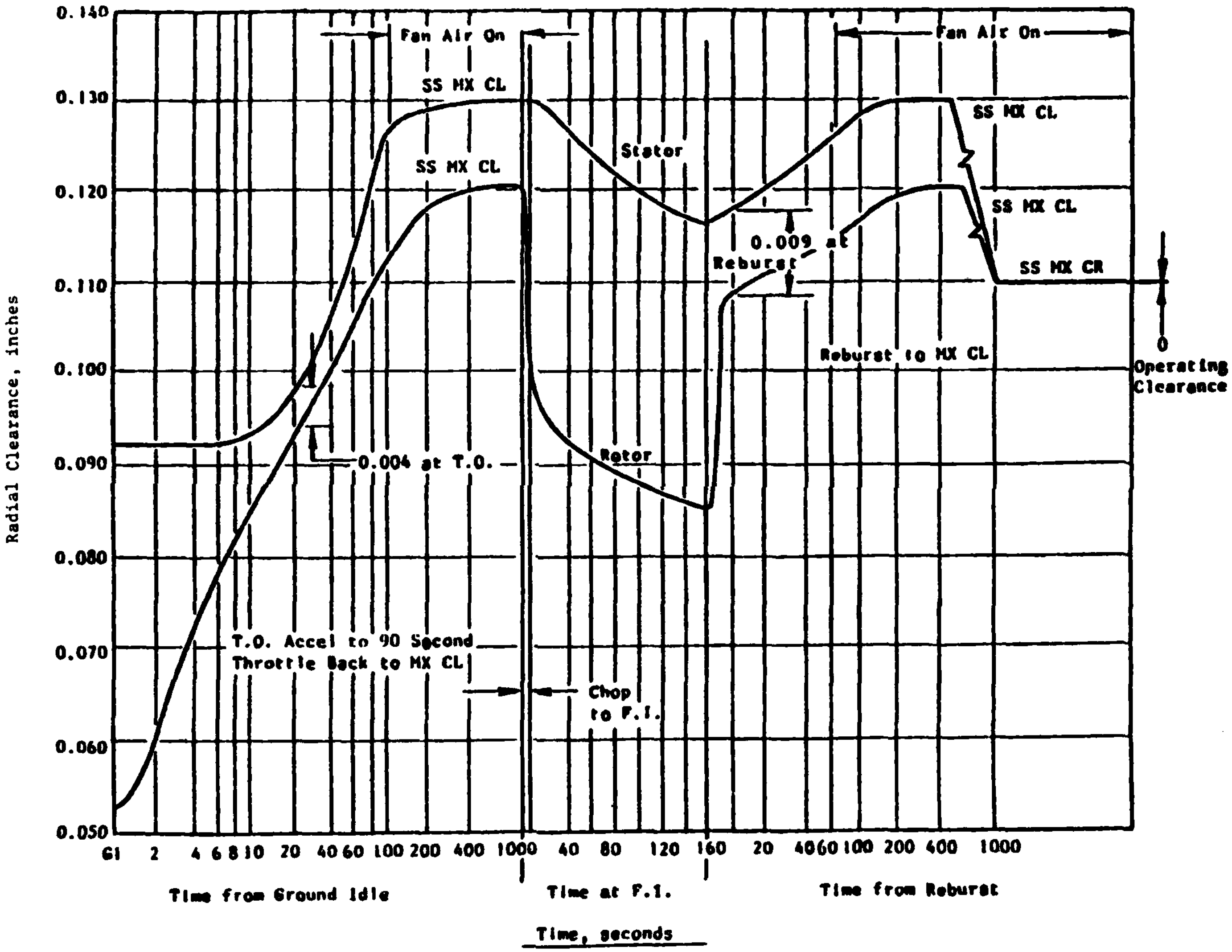


Figure 35. CFM56 Rotor-Stator Signature 0.01% Fan Air with No Air at 7.0.

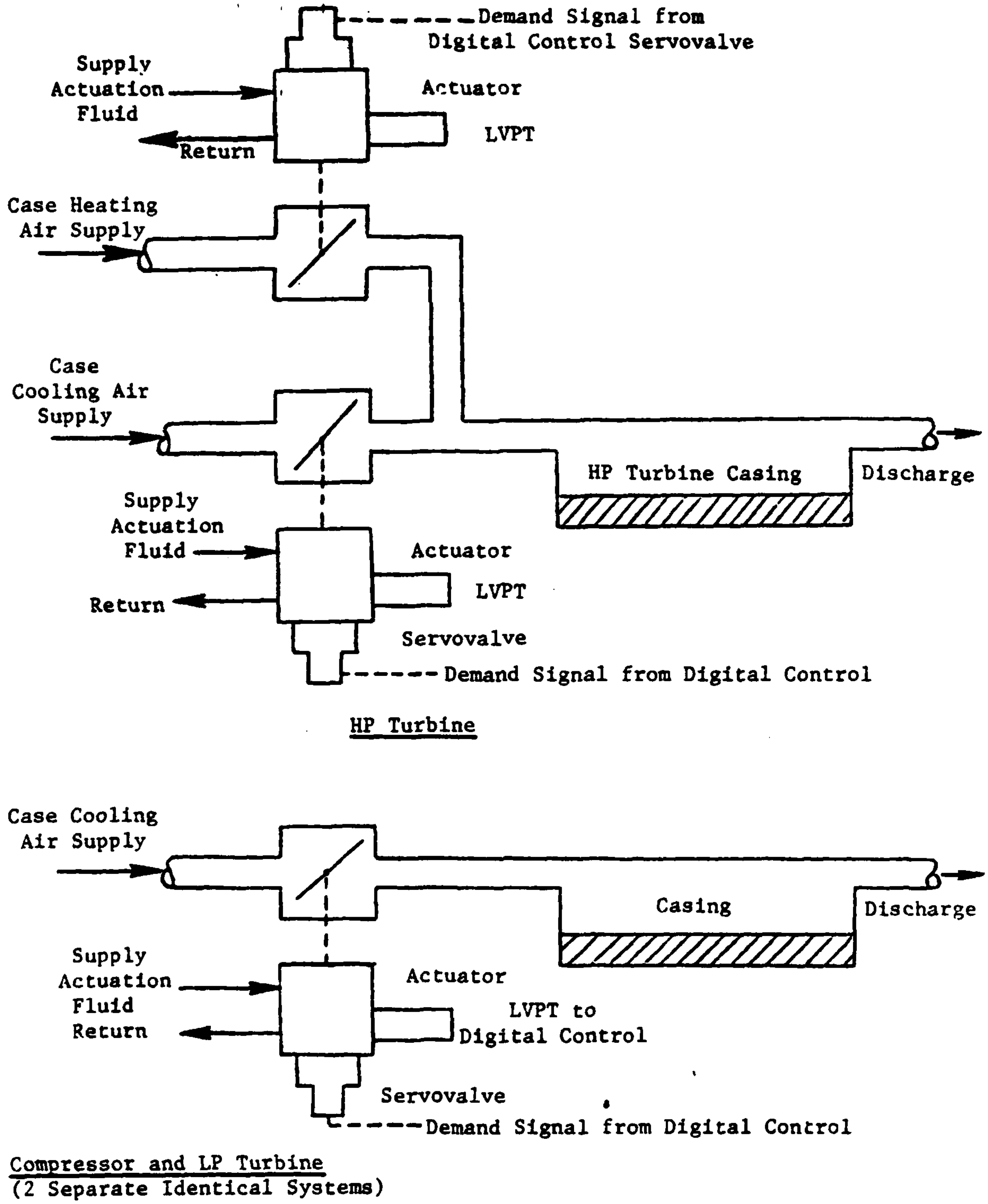


Figure 36. Preliminary Active Clearance Control Systems.

A block diagram showing one approach to alternative 3 is given in Figure 37. In this approach, dynamic models of the rotor and shroud will be incorporated in the digital control memory. These models will provide continuous, dynamic calculation of rotor and shroud diameters. Shroud model accuracy would be enhanced by sensing shroud temperature, comparing it to the equivalent temperature calculated by the model, and adjusting the model to minimize the difference.

The digital control calculates clearance by subtracting the rotor diameter from the shroud diameter. This clearance is compared to a scheduled clearance (shown here as a function of core speed, engine inlet pressure, and core speed rate of change), and the air valve or valves are moved to get the desired clearance.

The control approach just described is only one of several clearance control possibilities. The detail design requirements (obtained from heat transfer studies) dictated the type of active clearance controls necessary for each engine. As this data became available, active clearance controls were tailored to fit each engine application.

Studies conducted by the heat transfer personnel indicated that the concept for controlling the clearance control valves could be simplified and be scheduled for rpm and operating condition with compensation for thermal lags (Type 2 control alternatives). This system proposes the use of two-position (on-off) air valves that are controlled by a solenoid valve and a hydraulic actuator (Table 10) summarizes the requirements for each of the engines.

The preferred failure mode in all cases is to the closed valve position; i.e., the cooling air is turned off. This will give the largest clearance, thus minimizing the chances of a rub.

The cooling flow required is in addition to the normal cooling flows required for the engine.

A schematic of the CFM56 HP turbine clearance control system is shown in Figure 38. Its operation is the same as the CF6-6 turbine clearance control. The existing power management control will be modified to reflect the control strategy.

3.2.4 System Payoff

Determination of the fan air cooling ACC system concept for the CFM56/F101 allowed layouts of the piping configuration to be made, casing plus piping weight and costs to be calculated, and control costs and weights to be evaluated.

The CFM56/F101 casing weight and cost penalties imposed for fan air ACC are very small since only slight configuration changes were required to the present engine casing design. The piping required was laid out as shown in

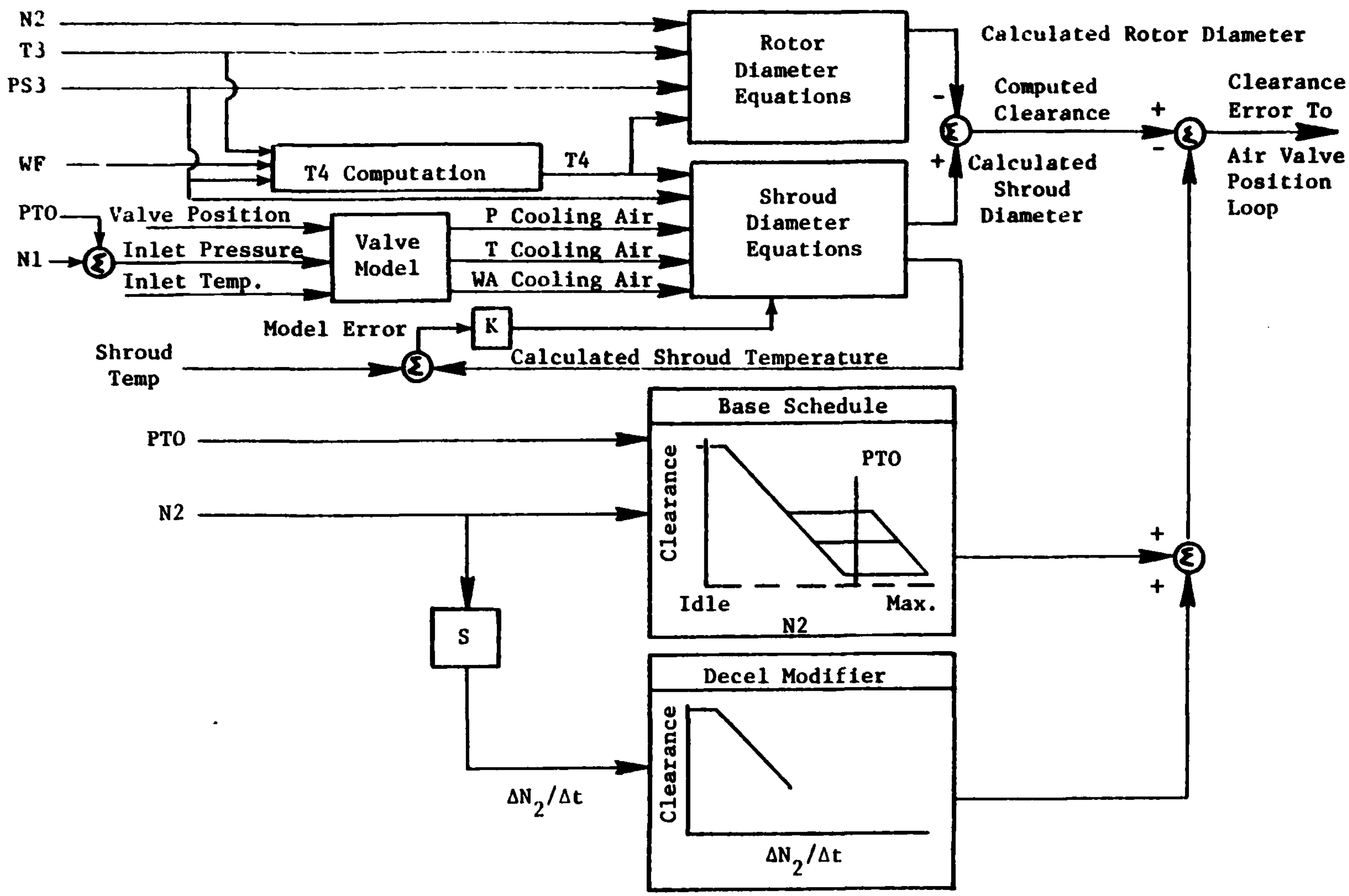


Figure 37. Preliminary Active Clearance Control.

Table 10. CFM56/F101 Control System Requirements.

Engine	Component	Air Supply System	Preferred Failure Node	Maximum Flow ($\%W_{25}$)	Minimum Flow ($\%W_{25}$)	Supply Line (in.)	Control Logic	Actuation System
CFM56	HP Turbine	Fan (Active)	Closed	0.3	0	2.5	*	Solenoid Valve and Fuel Powered Actuator
	LP Turbine	Fan (Passive)	---	---	---	---	---	None
F101	HP Turbine only which is the same as the CFM56.							

*Control logic - There are two conditions when the cooling air will be switched on:

1) If core speed is above minimum cruise and below maximum climb and the altitude is greater than 16,000 feet, cooling air will be switched on.

2) If core speed is at or above maximum climb and case temperature is above a predetermined value, cooling air will be switched on. Cooling air will remain on until speed drops below the maximum cruise level.

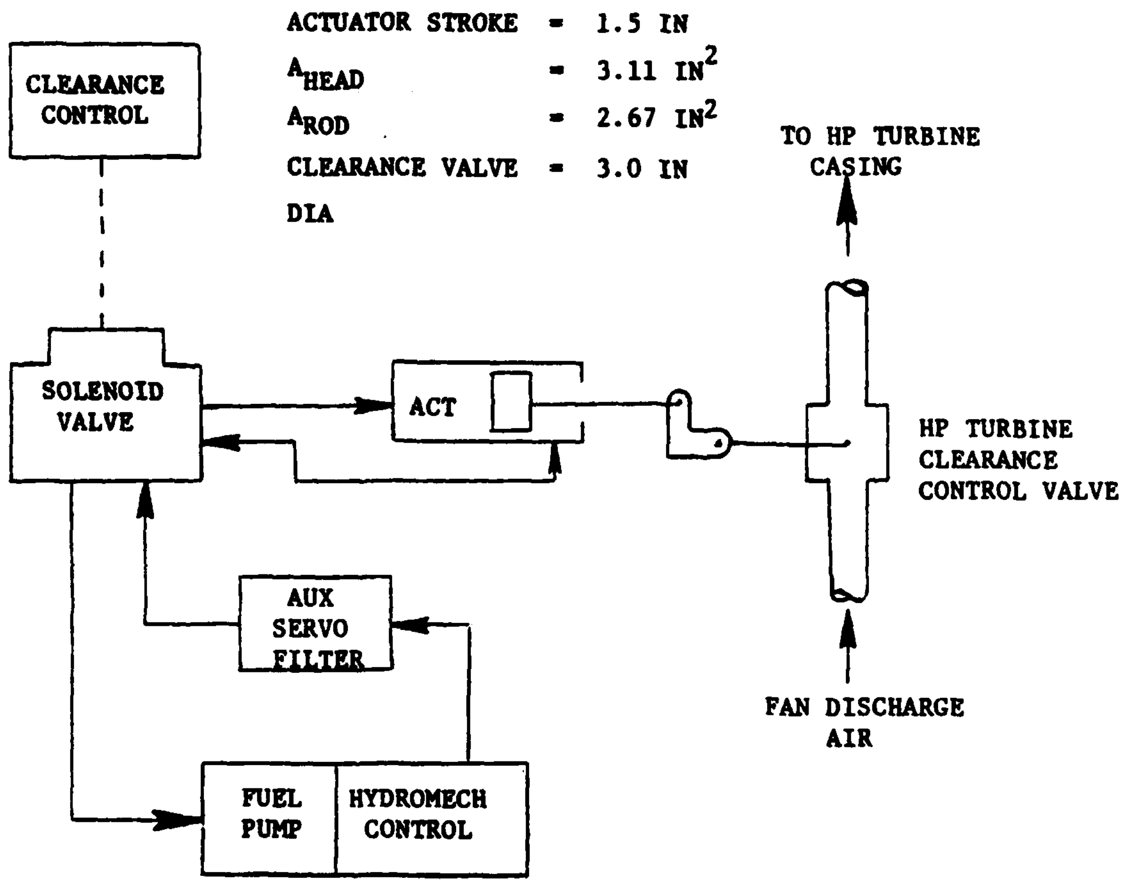


Figure 38. CFM56 HP Turbine Clearance Control System.

Figure 39 and also involved small weight and cost increases over the present design for the same reason. Detailed weight changes and cost differences (on the basis of production quantities) are given in Table 11.

Phase III of the control study was directed at weight and cost studies for each of the engine applications. Since each of the systems was simplified to a "type two" system, an analog box was selected for the electrical control logic. The reasons for this are two-fold:

1. The relatively simple control logic
2. Proven flight test experience on a commercial engine (CFM56 power management control)

A trade-off study was conducted if the control logic should be hydromechanical or electrical. The electrical logic was chosen because it was $1500 less and 2 pounds lighter. Fuel powered actuators were chosen because of the simplicity of design and the availability of a high pressure source (pressure pump discharge). Table 11 summarizes the control system weight and cost breakdown.

In summary, the active clearance control design selected should prove to be a simple, rugged, reliable system using only existing technology and hardware.

3.2.4.1 CFM56 - Commercial

Evaluation of the payoff of each engine system involves calculation of the individual factors which then are weighted correspondingly for their effect on overall payoff and summed into a total figure of merit.

For the CFM56 Commercial mission, the figure of merit is direct operating cost (DOC) whose major contributing factors are change in fuel efficiency (Δsfc), change in weight, and change in cost. When viewed as a summation factor, the Δsfc of -1.78% is due to clearance improvement, a savings in 5th stage cooling air and a small penalty for fan air used. The net weight increase of 0.74% is due mainly to the fan air manifold and control valves and the cost increase of 0.71% is also largely effected by the same factors. The net DOC is evaluated as follows:

$$\text{DOC} = 0.397\ \Delta\%\ \text{sfc} + 0.026\ \Delta\%\ \text{Wt.} + 0.100\ \Delta\%\ \text{Cost}$$

$$= -0.706 + 0.019 + 0.071 = -0.616\%$$

This improvement is significant and is discussed in the Conclusions section.

3.2.4.2 CFM56 - AWACS

The figure of merit for the AWACS extended aircraft mission is ΔTime-On-Station whose major contributing factors are change in fuel efficiency (Δsfc) at the major mission legs of cruise and loiter, and change in weight.

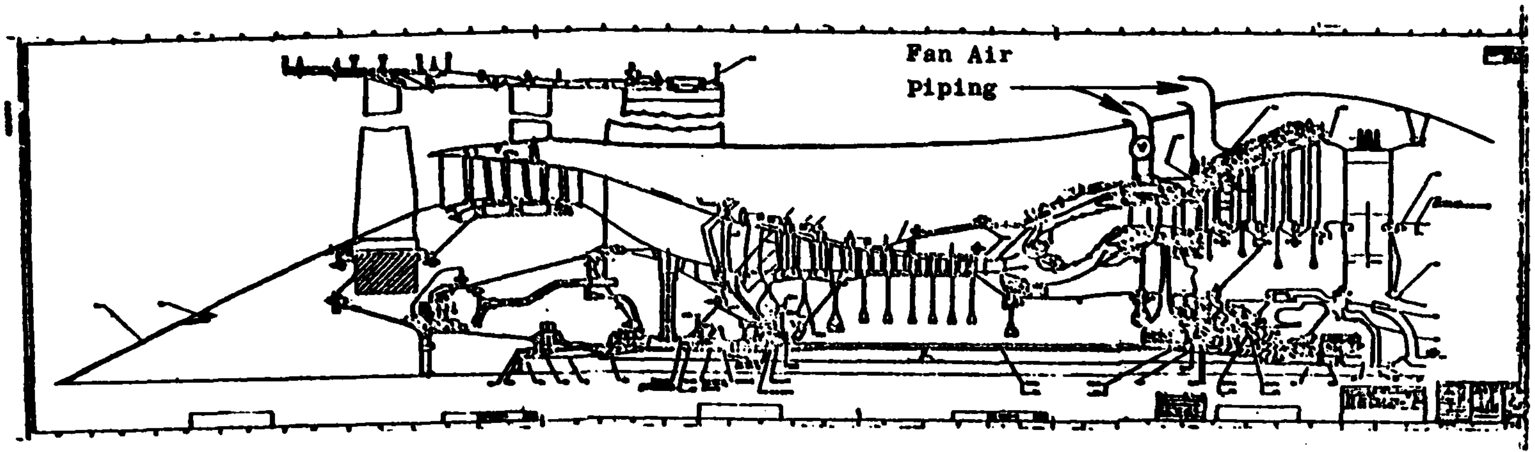


Figure 39. CFM56/F101 Piping Schematic.

Table 11. CMS56/F101 Turbine ACC Modification Cost and Weight Changes.

Hardware	Qty.	Added Weight (% of Total Engine Wt)	Added Cost (% of Total Engine Cost)
Casing	1	0.03	0.08
Manifold	1	0.11	0.06
Bushings	6	0.06	0.01
Piping	-	0.26	0.06
Controls			
- Electrical Control	1	0.03	0.09
- Actuator	2	0.21	0.37
- Fuel Lines	-	0.04	0.04
		0.74%	0.71%

The weight is 0.74% with Δ% sfc's of -1.812 at cruise and -1.828 at loiter combined in the payoff calculations. The net ΔTime-On-Status is evaluated as follows:

$$\Delta\text{Time-On-Status} = \underset{\text{(Cruise)}}{-0.27\ \Delta sfc} - \underset{\text{(Loiter)}}{1.00\ \Delta sfc} - 0.17\ \Delta\%\ Wt.$$

$$= 0.49 + 1.828 - 0.127 = +2.19\%$$

3.2.4.3 F101 - Bomber

The F101/bomber figure of merit is Δrange whose major contributors are Δsfc and Δweight. Weight increase is also 0.74% (shown in Table 11) but Δsfc due to improved cruise clearance and increased fan air is -1.95% and are offsetting factors in payoff calculations. Net Δrange is as follows:

$$\Delta\text{Range} = -0.392\ \Delta\%\ sfc - 0.072\ \Delta\%\ Wt.$$

$$= 0.765 - 0.065 = +0.700\%$$

3.3 CF6-6 TURBINE

Major emphasis was placed on the high pressure turbine because of significant clearance benefits identified in earlier studies. As with the CFM56/F101 study, the basic configuration chosen in the Concept Selection Study was carreid into further evaluation by heat transfer, mechanical design, and controls.

3.3.1 Heat Transfer Design and Analysis

During this program one concept was given detailed heat transfer analysis to determine the potential clearance control benefits. This concept is shown in Figure 40. The 1st stage high pressure turbine shrouds are hung from casing-mounted rings. The thermal growth of these rings governs the shroud growth. Two methods of varying the ring temperatures were investigated. First, CDP air could be run through passages in the rings while on the way to cooling other components. Secondly, fan discharge could be impinged on the outside of the rings. In the end, a combination of these two methods turned out to be best for transient tip clearance control.

Preliminary hand calculations showed that a passive CDP air system could provide a good stator-to-rotor growth match during transients. A very similar passive 13th stage air clearance control system has worked well for the current CF6-6 second turbine stage. However, extra cooling was needed on the rings for tighter clearance during cruise to optimize performance. Previous General Electric analyses had shown that relatively inexpensive, low temperature fan discharge air would serve best for ring cooling. The fan discharge air would be turned on only when needed at cruise.

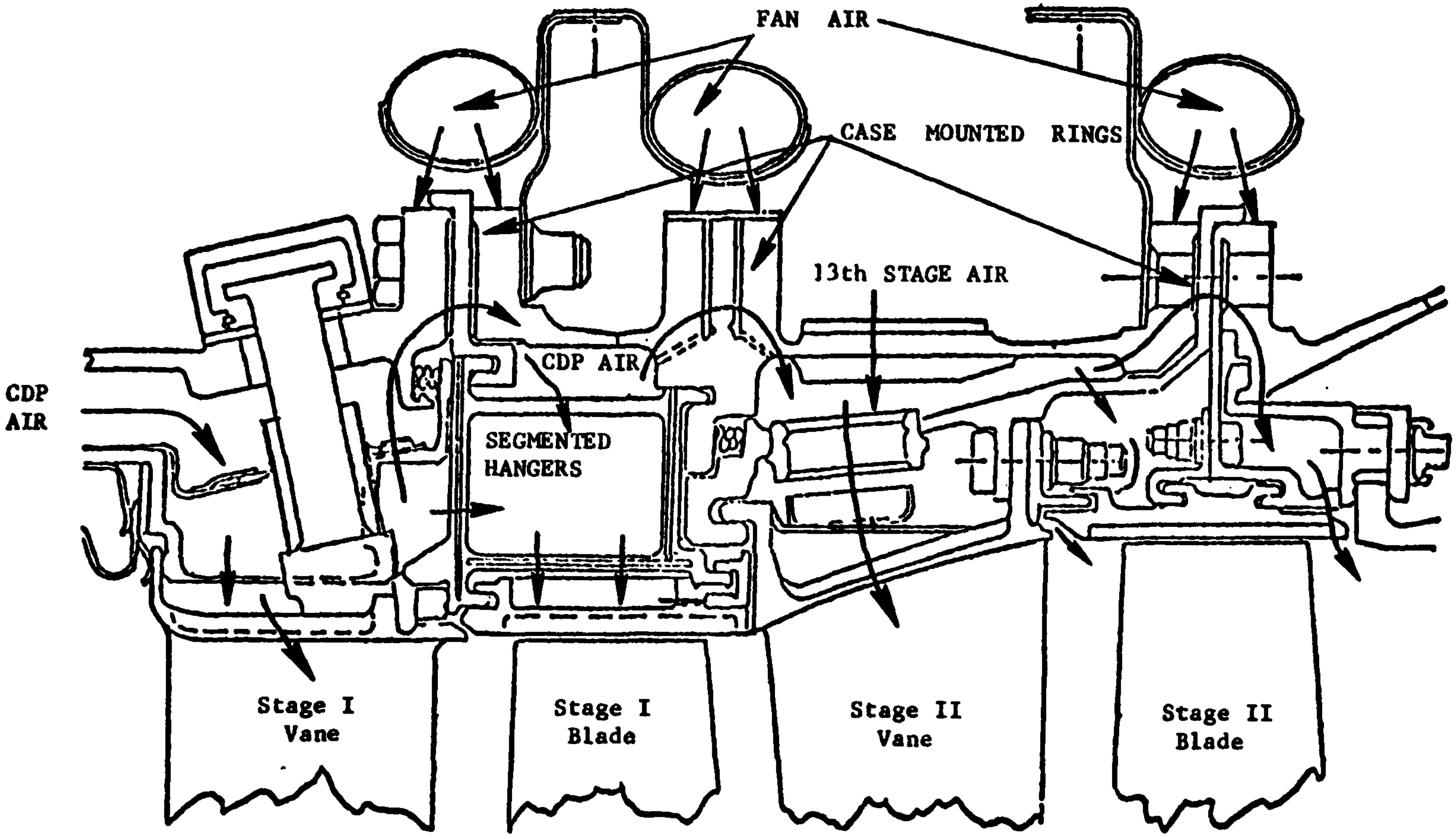


Figure 40. CF6-6 HPT Case Mounted Clearance Control System.

Figure 41 is a detailed nodal model for the heat transfer analysis of the high pressure turbine stator by means of the THTD computer program. Preliminary runs were made to check out the model and to refine the geometry, proposed flows and miscellaneous model details. The resulting model was then run through the selected mission, shown on Figure 42. Transient temperature distributions were provided for growth calculations to check tip clearance at cruise and the most likely transient rub points. A takeoff accel and four different hot rotor rebursts were run in the mission to ensure any potential rub problems would be found. The steady-state and transient boundary condition given to the computer were based on CF6-6 test data.

Four basic cases were run with THTD: CDP air only, fan air only, a base case with neither source used, and finally with both flows turned on. All four cases were run through the entire mission. Thus, the benefits of CDP air and fan discharge air could be judged both independently and together. Combinations such as only CDP air during transients and CDP air plus fan discharge air at cruise could be checked by splicing together the results of different cases. Table 12 shows the computer runs which were made. Figures 43 and 44 show typical results.

The variety of heating and cooling flows studied ranged from 0.2 to 1.2% W_{25} of CDP air and from 0.1 to 0.4% W_{25} per ring of fan discharge air. After interfacing with mechanical design clearance results, the proposed flows (Table 13) were obtained by using CDP air only to match the thermal response rates of the rings to the disk. The fan discharge airflow turned on at cruise (while the passive CDP air system still flowed) was sized to give the minimum possible cruise tip clearance.

Estimates were made of the piping required to deliver the fan discharge air to the turbine area. These pipes were used in calculating weight penalties. One 2.5 inch diameter pipe could deliver the fan air to a bird cage with two rows of (314) 0.035-inch holes impinging on each ring. The CDP air slots are 0.6 x 0.035-inch with 22 inlets and outlets.

The heat transfer conclusions drawn from the study were:

- Case-mounted shroud support rings could effectively use both CDP and fan air for high pressure turbine tip clearance control.
- Fan air in an on/off impingement cooling system can significantly reduce shroud support ring temperatures.
- CDP air passing through grooves in the rings on its way to cool the shroud and Stage 2 vane could be used to increase ring temperature transient response.
- Suitable CDP flows for the CF6-6 Stage 1 flanges were 0.4% W_{2C} which also replaced 0.3% 13th stage air in the Stage 2 flange. 0.3% W_{2C} fan air was used externally.

3.3.2 Mechanical Design and Analysis

As in the CFM56/F101 mechanical analysis, the CF6-6 HPT clearance plots were approached using the current rotor growth signature and matching the stator signature to the rotor.

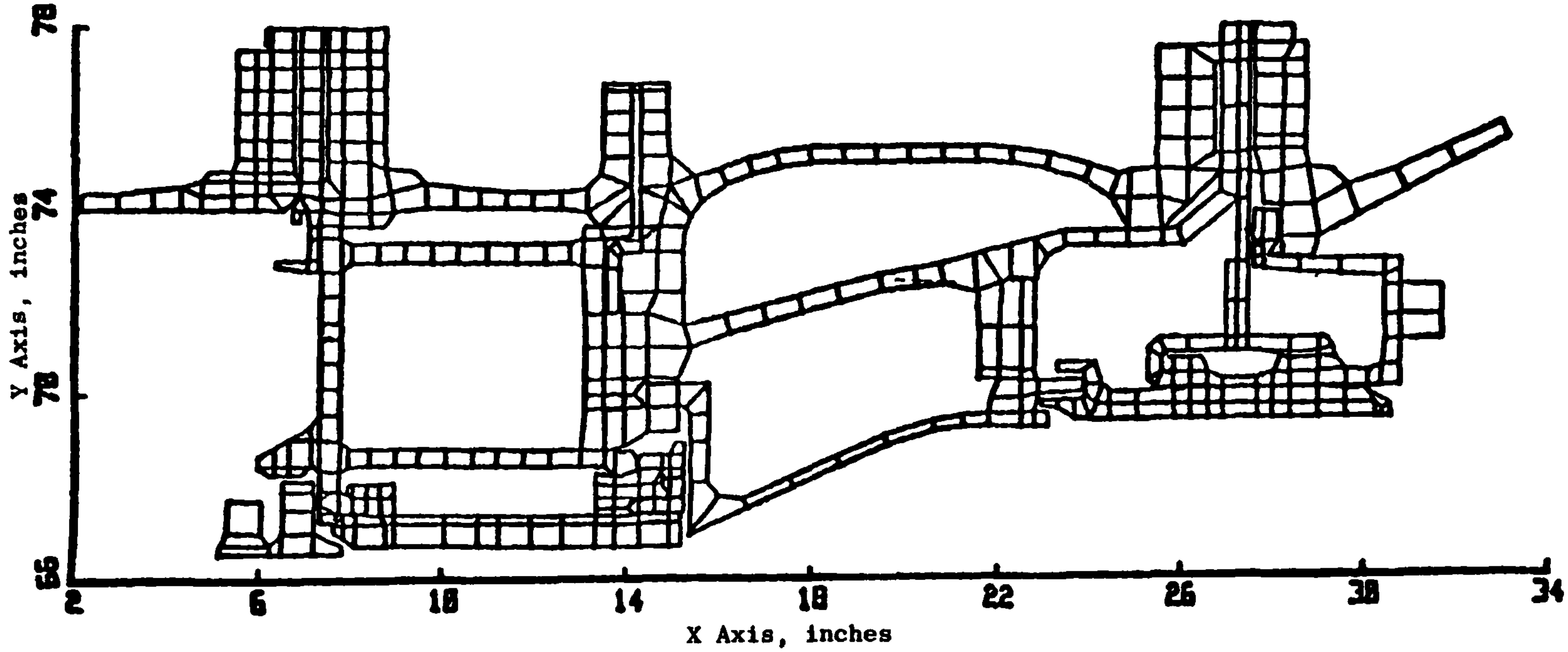


Figure 41. CF6-6 Turbine THTD Model.

- Cycle Points Consistent with Performance Studies
- Transients Based on CF6-6 Test Data

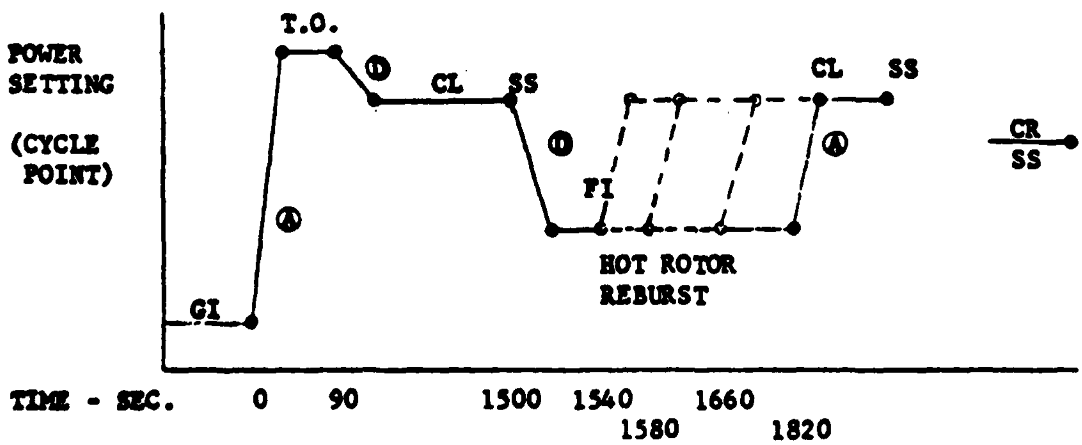


Figure 42. CF6-6 Mission Profile.

Table 12. Thermal Cases Run for CF6-6 Turbine.

	Accel	Decel	40 sec. Reburst	80 sec. Reburst	160 sec. Reburst	320 Sec. Reburst	SS Cruise
Heat Only	X	X	X	X	X	X	X
Heat & Cool	X	X	X	X	X	X	X
Cool Only	X	X	X	X	X	X	X
No Heat/No Cool	X	X	X	X	X	X	X

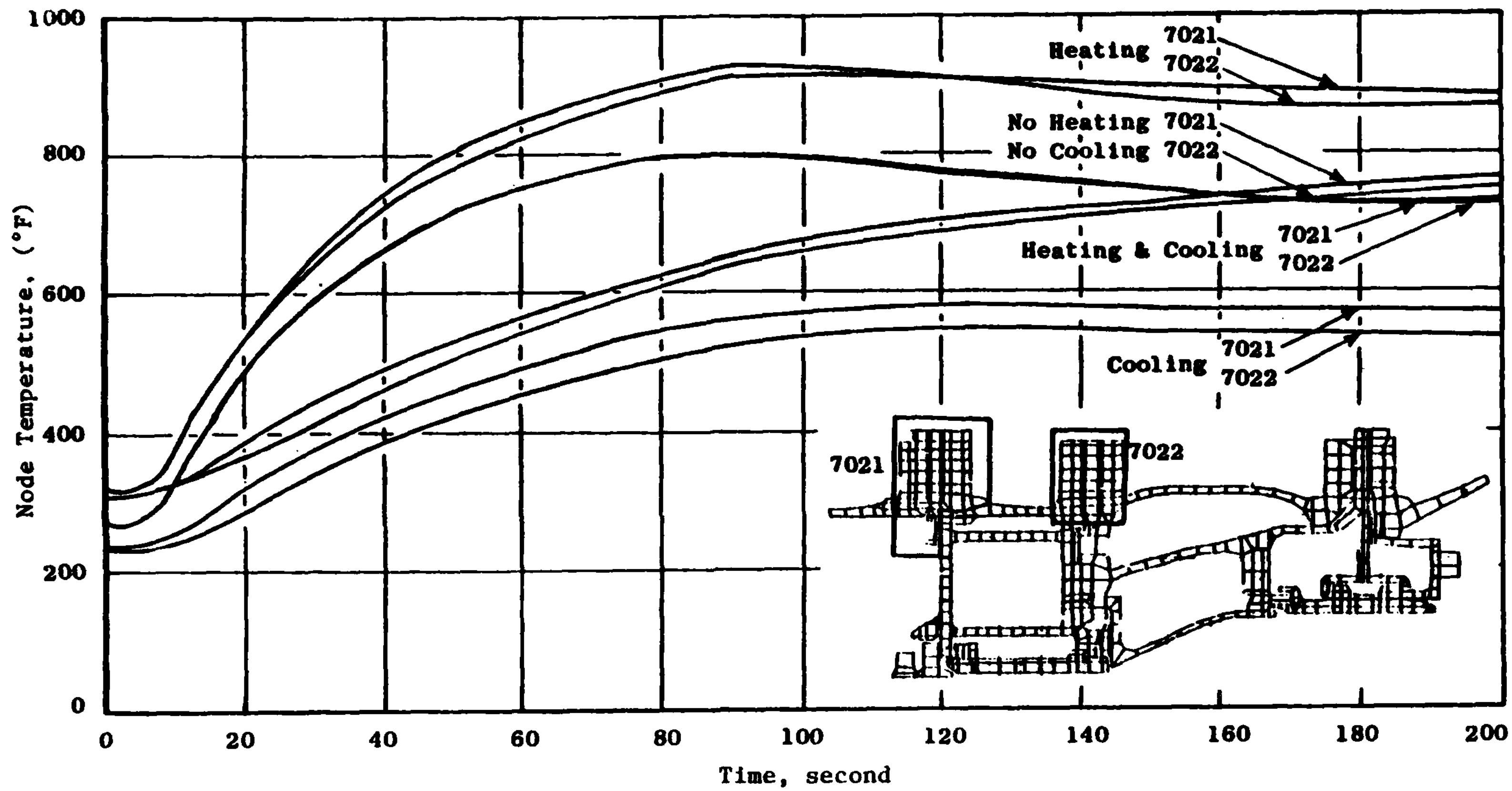


Figure 43. CF6-6 Turbine Transient Temperature Response.

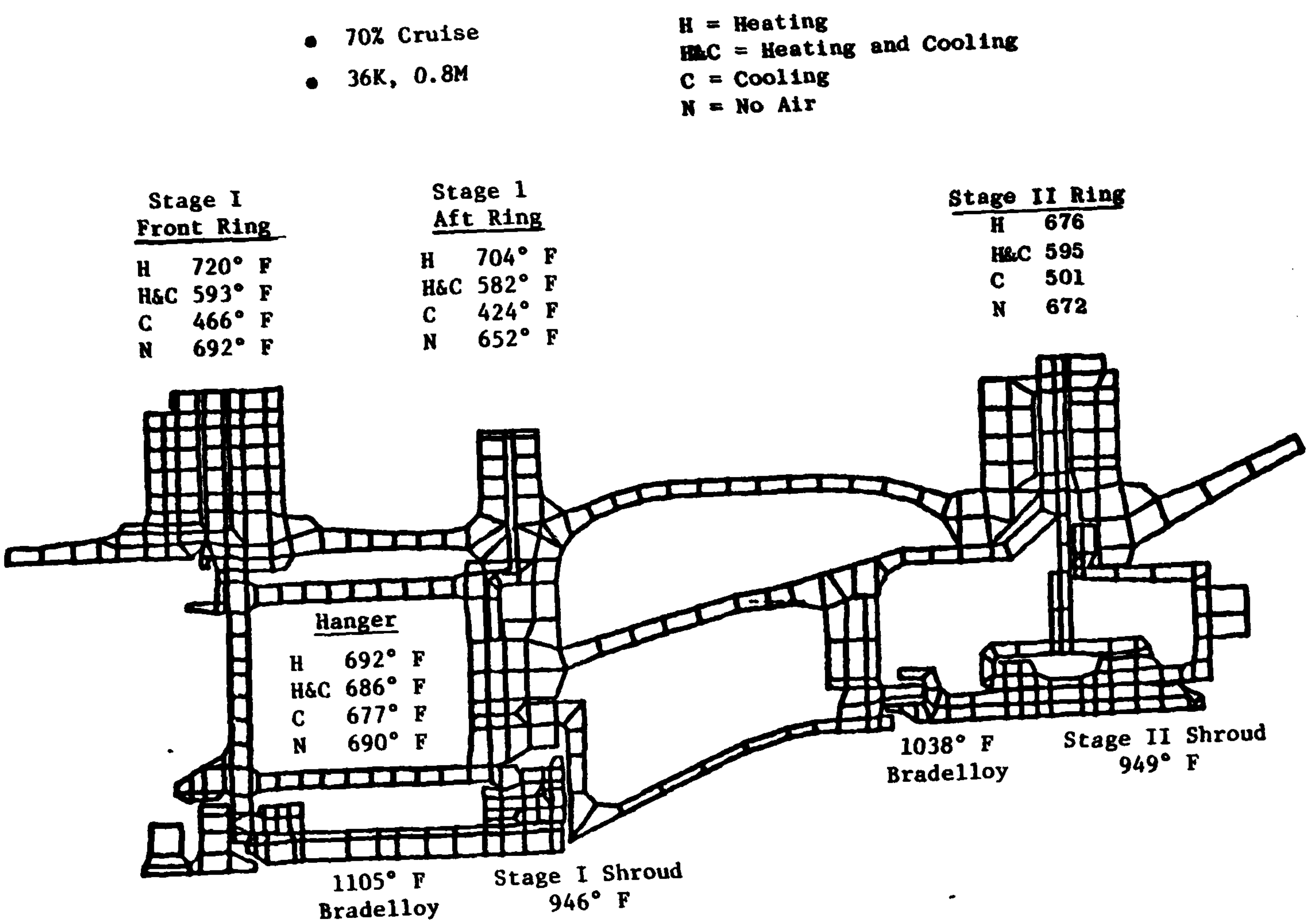


Figure 44. CF6-6 Turbine Steady-State Temperatures (° F).

Table 13. Clearance Control Air Supply Candidates.

	W (% W_{25})	$T_{T\,0}$ (° F)	T_{Cruise} (° F)
CDP	0.4 for Stage 1	1017	740
13th Stage	0.2 for Stage 2	855	625
Fan	0.1 per Ring	175	51

The baseline current CF6-6 HPT clearance profile, when sized for close cruise clearances, encounters transient rubs during takeoff. These rubs are due to the combined effects of out-of-round transient loading, external pressure deflection, and uneven midframe thermal heating. The new case-mounted ring concept addresses improved roundness through increased stiffness, elimination of high external pressure, and isolation of the midframe distortion.

To evaluate the transient clearances of the stator casing, a shell computer model was made for use with GE's CLASS/MASS computer program. Figure 45 shows the model that was constructed. The model was set up in conjunction with the THTD heat transfer model to directly utilize the calculated temperature distributions into the CLASS/MASS model. The basic heating/cooling cases were analyzed for accel and cruise as shown in Figures 46 (heated flanges with and without cooling) and 47 (unheated flanges with and without cooling). The same cases were analyzed for decel in Figures 48 and 49, and analyzed for reburst conditions (accel after a decel) in Figures 50 and 51.

The data showed that the rotor/stator touch point would occur during the takeoff transient and would not encounter rubs during decel or reburst. This was the desired feature in that the passive system would operate satisfactorily during transient and cooling closure would be carried out during steady-state cruise. The stator diameter at the 1000 second point is shown larger for the unheated case than for the heated. This is due, however, to the larger cold clearance of the unheated case in order to avoid rubs. The actual change in diameter from 1 second to 1000 seconds is smaller for the unheated (~70 mils versus ~80 mils) as would be expected.

In comparing the heated versus unheated designs, the heated concept is found to have closer passive clearances during cruise and climb with somewhat more overshoot at the end of takeoff. The heated concept would also allow closer cruise clearances when cooling is applied. A quantitative comparison of clearance along with the assessment of cooling air quantities/penalties is shown in Table 14. The values reflect refined cycle analysis weighting factors from those presented in early calculations. This table shows the heated flange with external cooling is the most effective design.

It is interesting to note that other program studies of similar trade-offs have shown the benefits of external cooling, but have indicated that the unheated flange is more effective. The key factor in determining whether heated or unheated is preferable appears to be the response rate of the rotor. For relatively light disks that respond quicker to thermal growth, the heated flange is a better choice, as in the CF6. Where heavier, less responsive disks are employed the unheated flange is a better match.

For the selected heated flange, externally cooled HPT configuration, piping layouts were made to route the fan air to the HPT as shown schematically in Figure 52.

3.3.3 Controls System

As a result of the heat transfer studies, the C&A requirements were established and are summarized in Table 15.

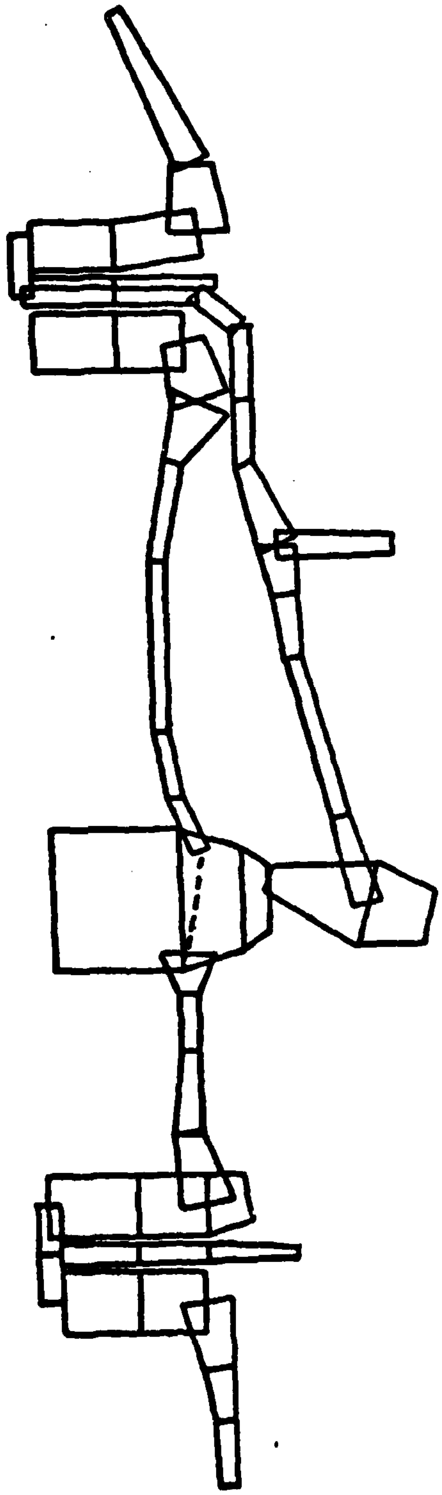


Figure 45. CF6-6 HPT Case CLASS/MASS Model.

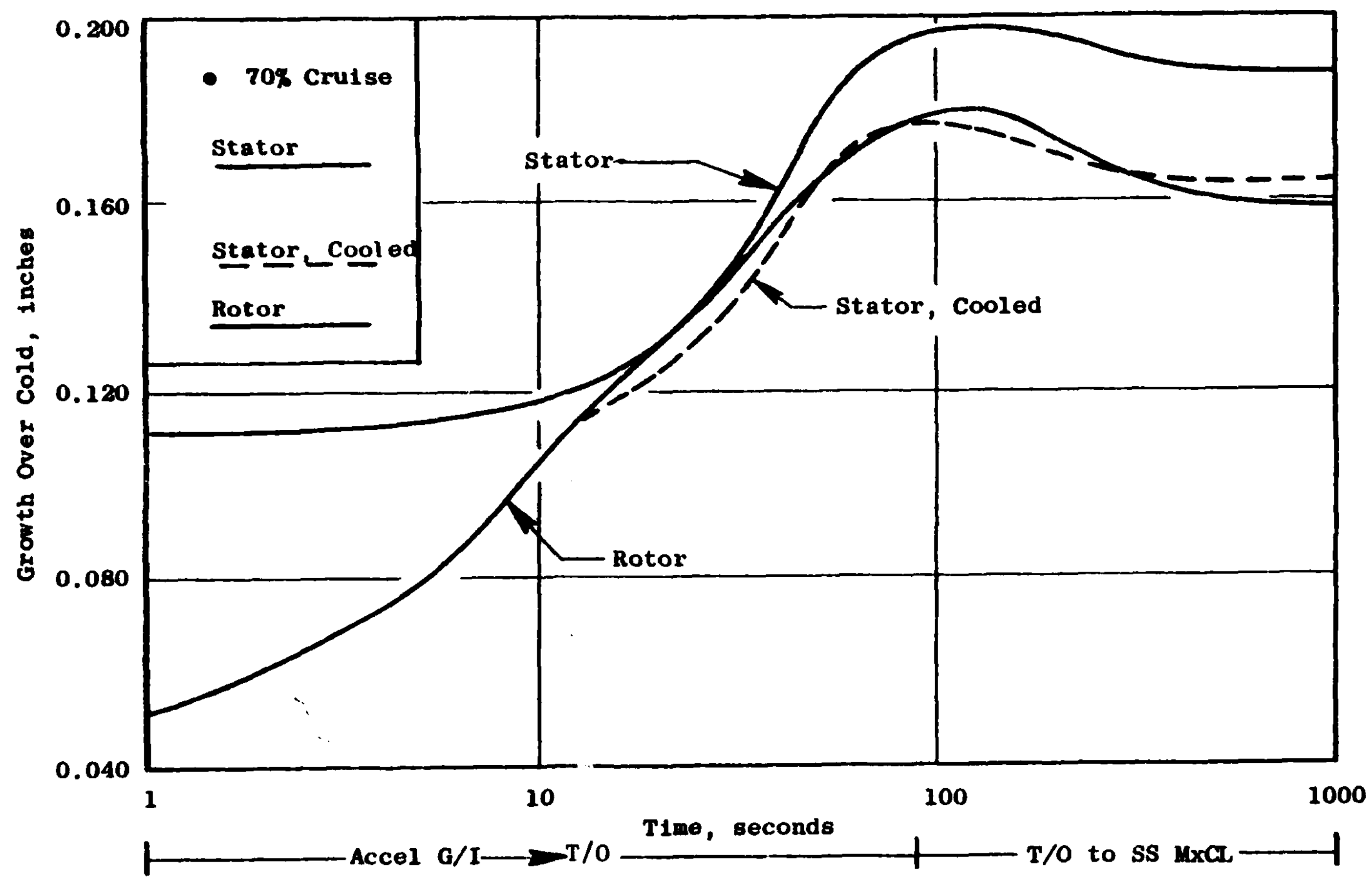


Figure 46. Modified CF6 Heated Flange Configuration - Takeoff, Cruise Conditions.

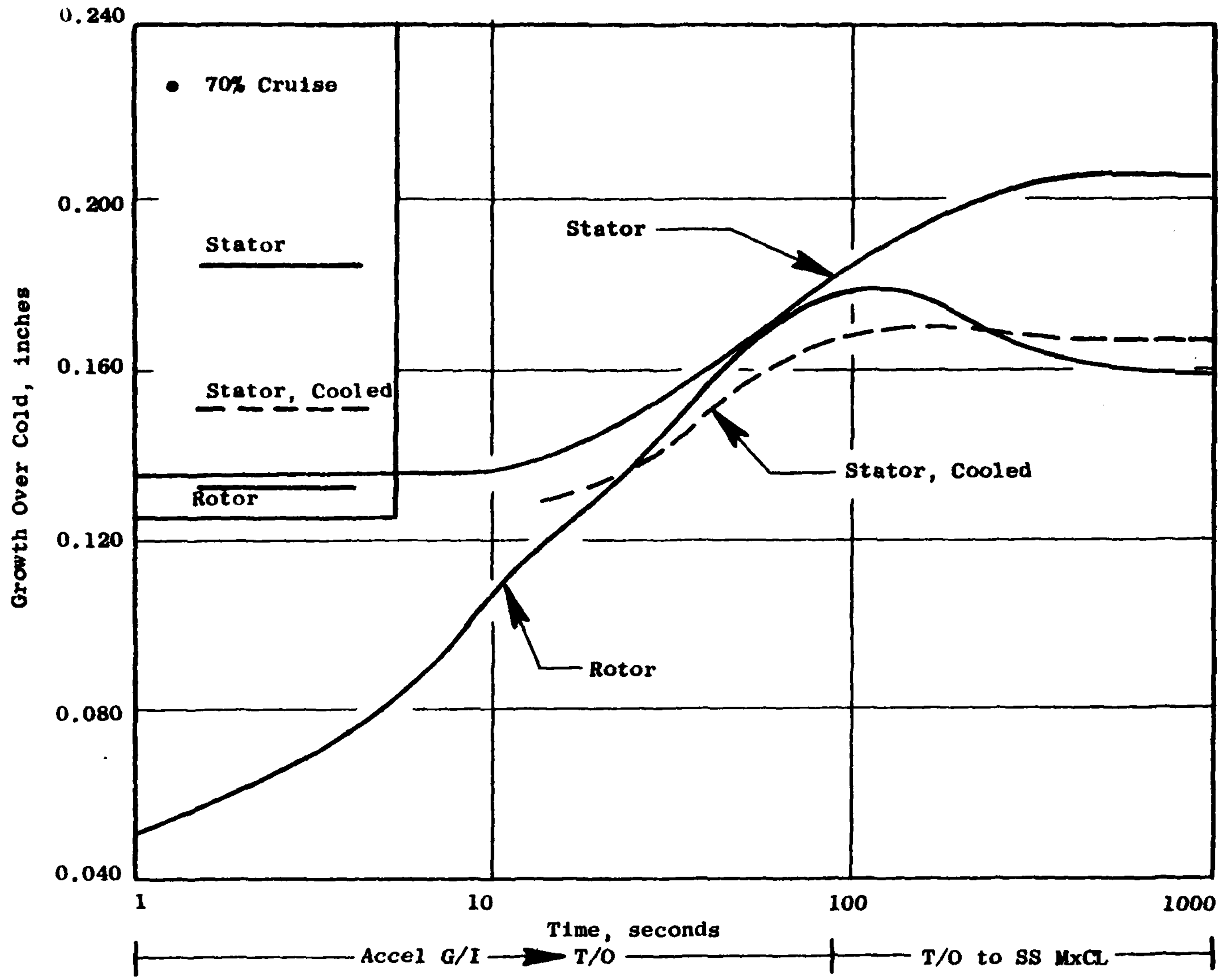


Figure 47. Modified CF6 Unheated Flange Configuration - Takeoff, Cruise Condition.

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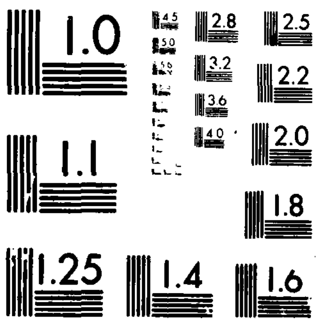

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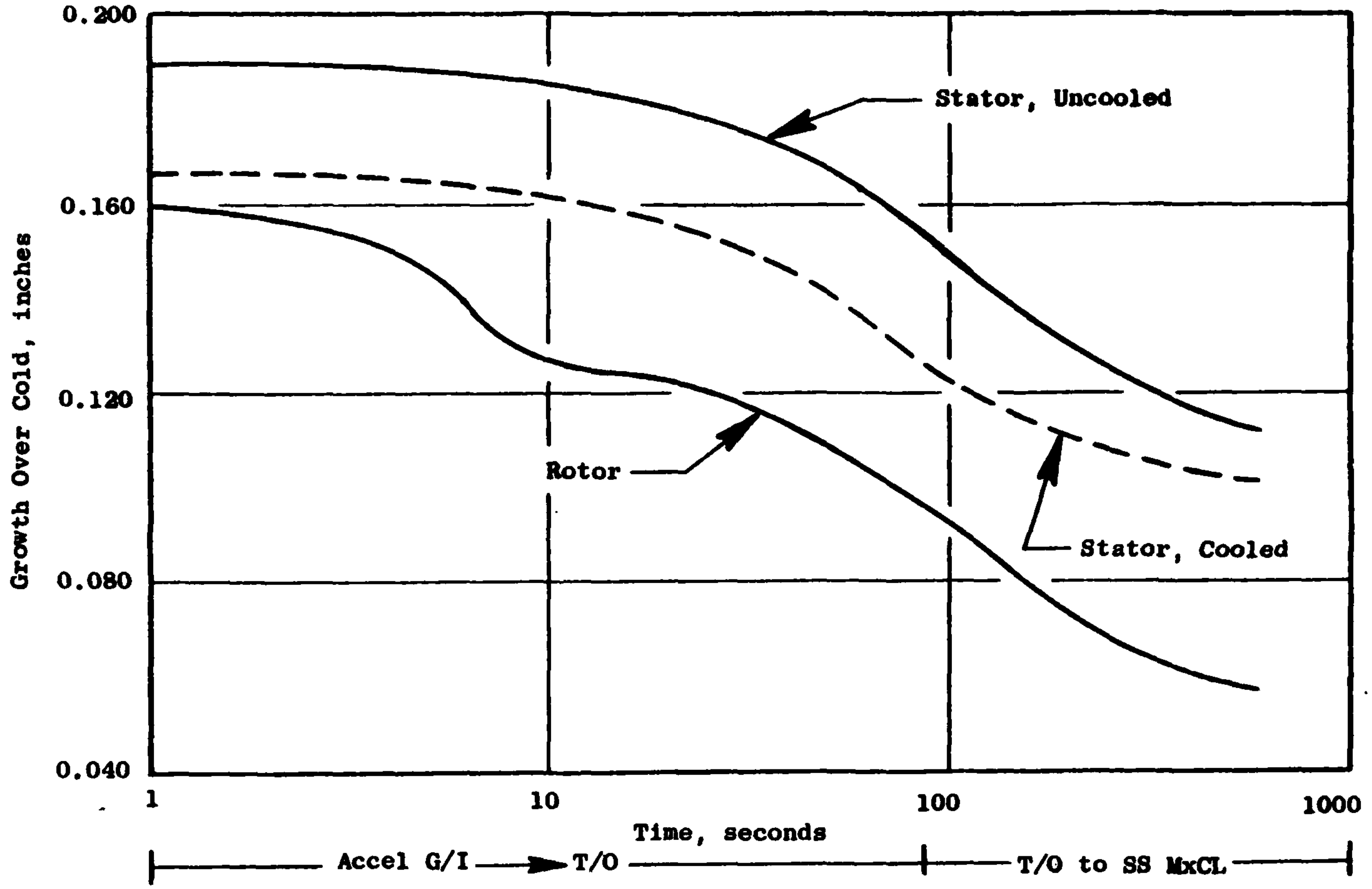

Figure 48. Modified CF6 Heated Flange Configuration - Decel Condition.

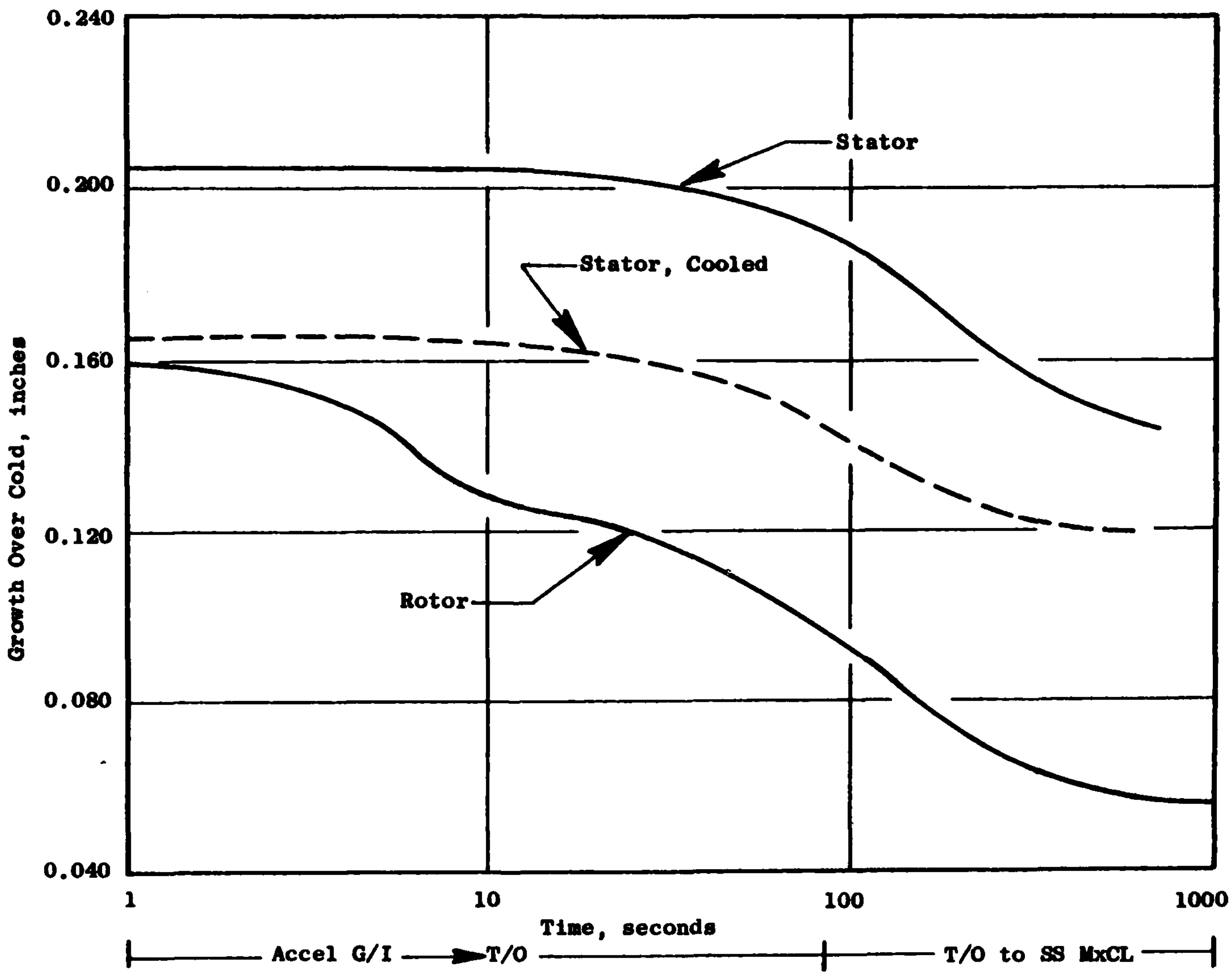

Figure 49. Modified CF6 Unheated Flange Configuration - Decel Conditions.

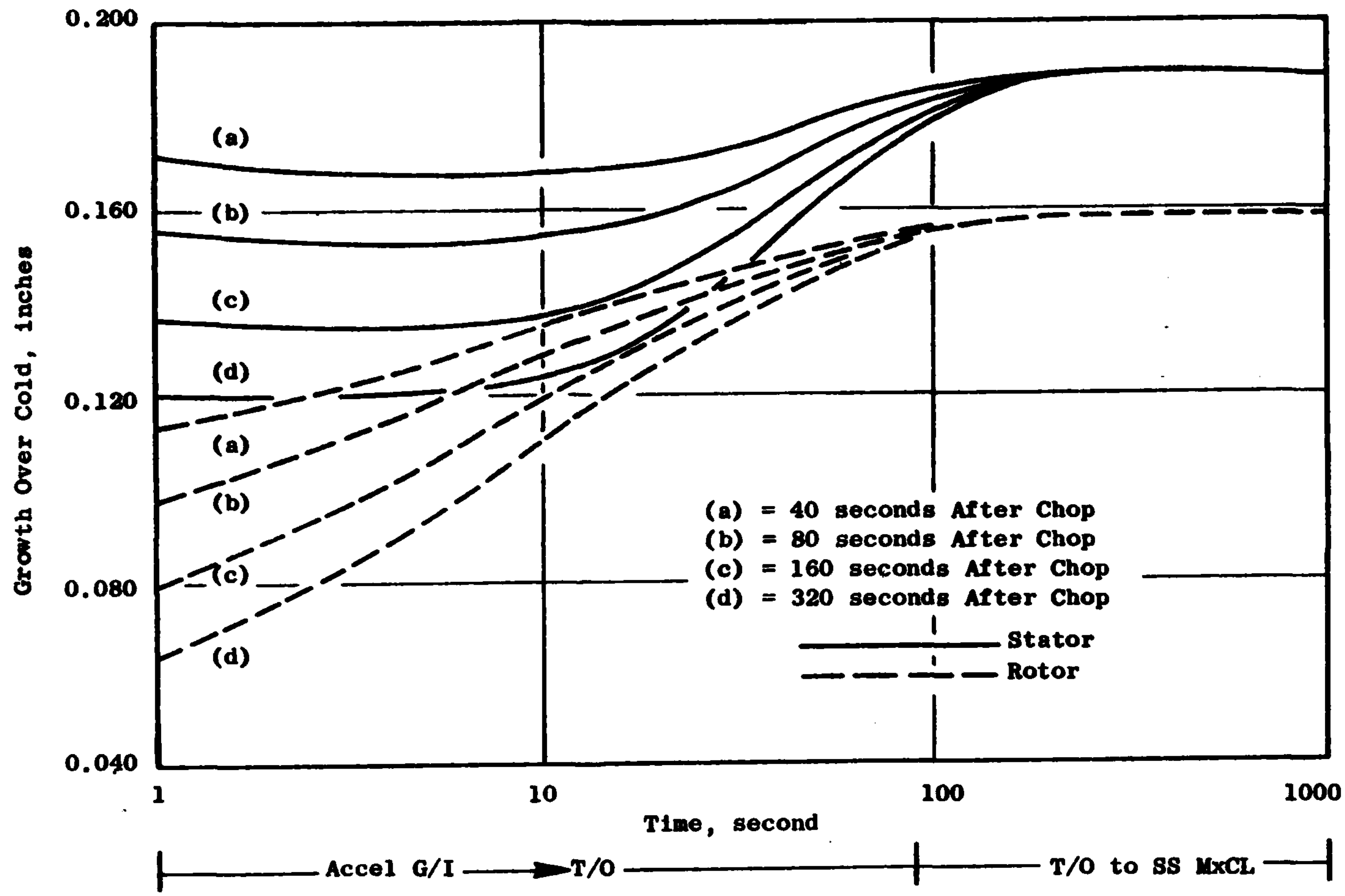

Figure 50. Modified CF6 Heated Flange Configuration - Reburst Conditions.

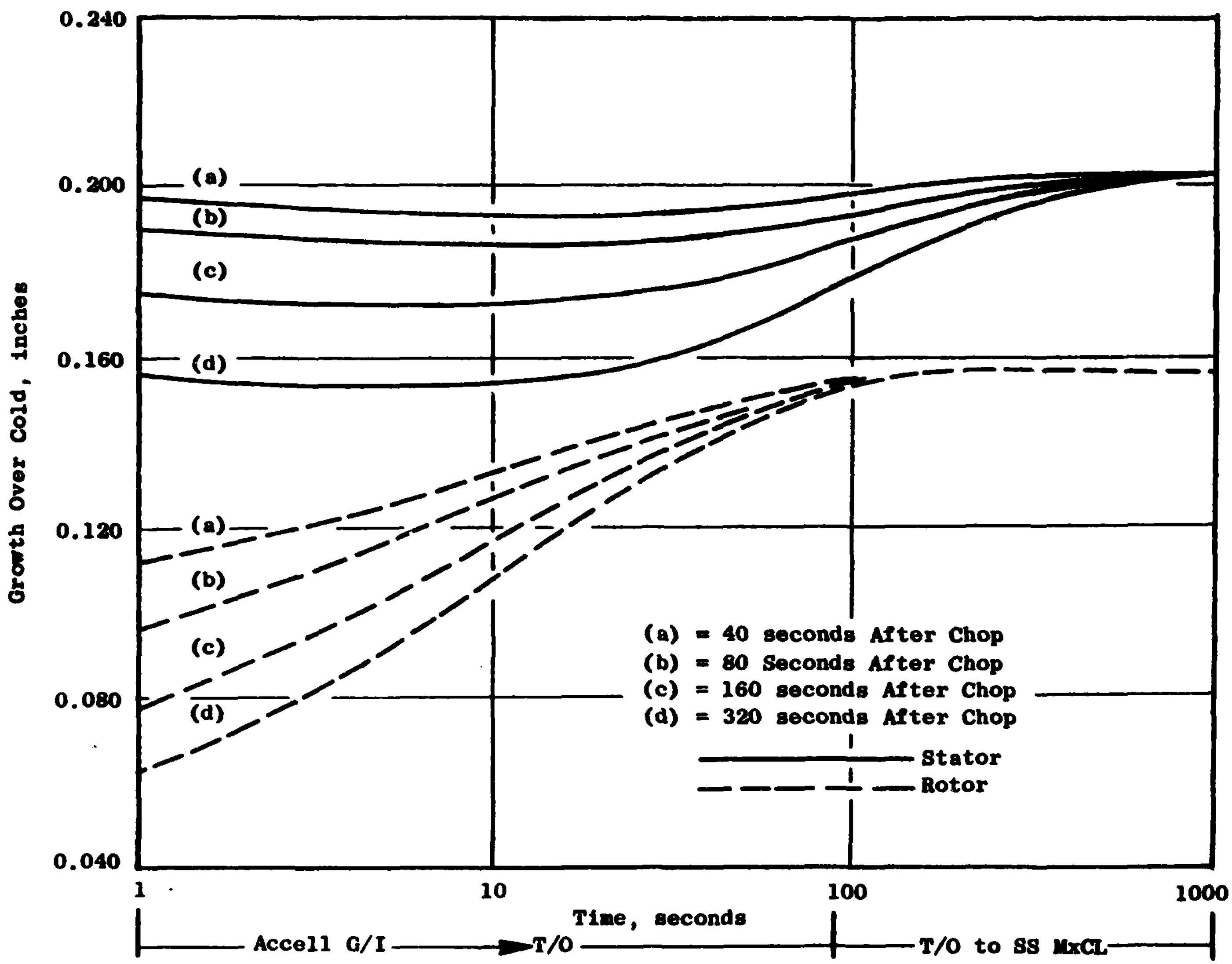

Figure 51. Modified CF6 Unheated Flange Configuration - Reburst Conditions.

Table 14. Δsfc Payoff Evaluation Modified CF6-6 HPT.

Configuration	Coolants (Δ%)			Cruise Clearance		SFC Δ%
	Fan	13th	CDP	Inches	ΔInches	(- Is Benefit)
Current CF6-6	0	Base	Base	0.034	Base	Base
Heated Flange No Cooling	0	-0.3	+0.5	0.033	-0.001	+0.14
Heated Flange With Cooling	+0.3	-0.3	+0.5	0.012	-0.022	$\boxed{-0.73}$
Non-Heated Flange No Cooling	0	+0.1	+0.1	0.050	+0.016	+0.94
Non-Heated Flange With Cooling	+0.3	+0.1	+0.1	0.019	-0.015	-0.53

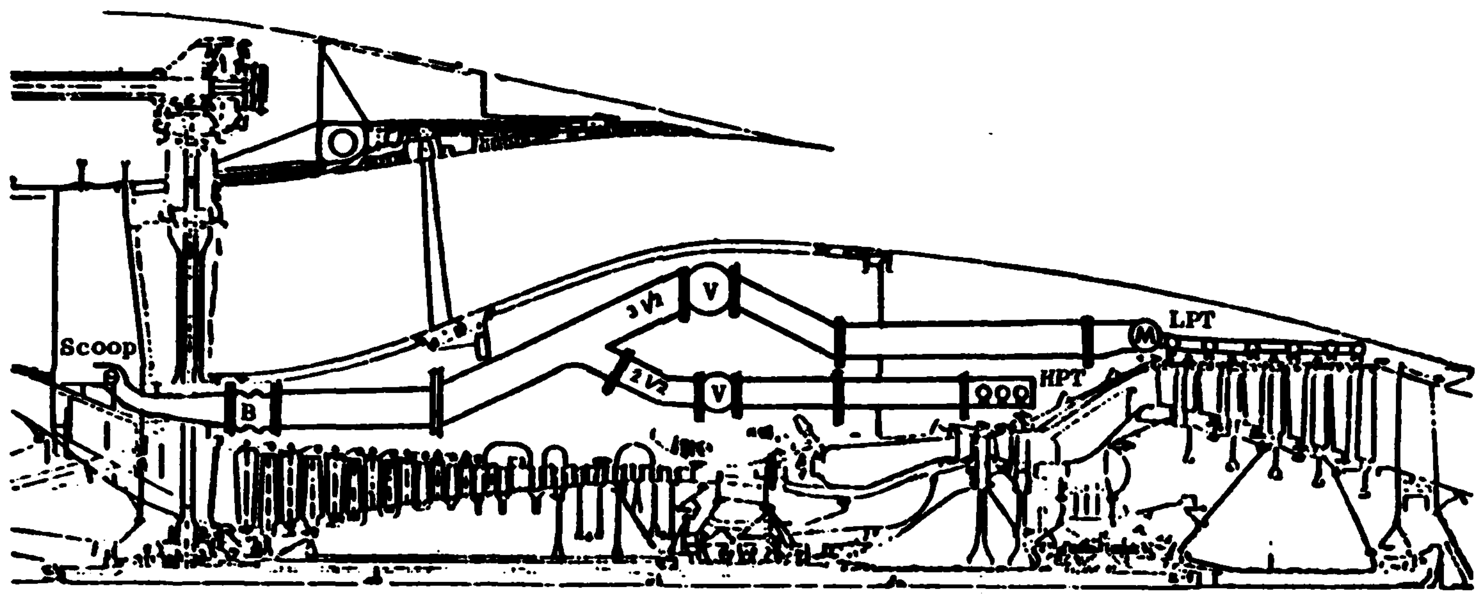

Figure 52. CF6-6 Active Clearance Control Piping Schematic.

Table 15. CF6-6 Turbine C&A Requirements.

Component	Air Supply System	Preferred Failure Mode	Flow (% W_{25}) Max.	Flow (% W_{25}) Min.	Supply Line Dia. in.	Control Logic	Actuation System
HP Turbine	Fan	Closed	0.3	0	2.5	*	Solenoid valve and fuel/powered actuator
LP Turbine	Fan	Closed	0.6	0.25	3.5	*	Solenoid valve and fuel/powered actuator

* Control logic - There are two conditions when the cooling air will be switched on:

1. If core speed is above minimum cruise and below maximum climb and the altitude is greater than 16,000 feet, cooling air will be switched on.

2. If core speed is at or above maximum climb and case temperature is above a predetermined value, cooling air will be switched on. Cooling air will remain on until speed drops below the maximum cruise level.

As in the CFM56/F101, the preferred failure mode in all cases is to the closed valve position, i.e., the cooling air is turned off. This will give the largest clearances, thus minimizing the chances of a rub.

The cooling flow required is in addition to the normal cooling flows required for the engine.

Two systems were considered in final control evaluation, both using hydromechanical controls for actuation but differing in that one used electronic logic and the other hydromechanical logic. Weight and cost studies were conducted on each of the systems and showed the electrical logic systems to be \$2,000 less and 1 pound lighter. Control weight and cost breakdowns are shown in Table 16.

A schematic of the CF6-6 turbine clearance control system is shown in Figure 53. The clearance control will receive input from an inlet pressure transducer (indication of altitude), thermocouple (case temperature) and the engine alternator (speed) and will send a 28 volt DC signal to the solenoid valves to turn cooling air on or off as required. The clearance control will be a separate analog device. The existing hydromechanical control will be modified to supply high pressure fuel to the solenoid valve. The actuator and clearance control valve will be fit in the cooling air supply line.

3.3.4 System Payoff

The system payoff study for the CF6-6 was aimed at a commercial mission utilizing a DC-10 3-engine type aircraft mission. The figure of merit decided upon for this application was DOC.

As with the CFM56 commercial mission, the CF6-6 commercial DOC is directly effected most significantly by Δsfc, Δweight and Δcost. Evaluation of these factors showed initial values as follows. Cruise benefits along with the effects of bleed air used resulted in a net Δsfc improvement of -0.724%. A breakdown of turbine weight and cost changes of the ACC configuration are shown in Table 16. The total weight effects of a modified HPT casing, added pipes, and valves were +1.17% with the cost of these modifications an increase of +3.64% in production quantities. The net DOC change from these modifications is as follows:

$$\Delta DOC = 0.364\ \Delta\%sfc + 0.022\ \Delta\%WT + 0.085\ \Delta\%COST$$

$$-0.267 + 0.026 + 0.310 = +0.069\%$$

This showed that although the clearance improvement and resulting Δsfc benefits were substantial, the penalties of weight were especially significant.

Subsequent work on this configuration under other programs has shown that control, cost, and weight reductions can be made by further refinements in design. These resulted in weight penalties of only +0.77% and cost penalties of +1.8%. The net ΔDOC = -0.267 + 0.017 + 0.151 = -0.099% or ~0.1%.

Table 16. CF6-6 Turbine ACC Modification Cost and Weight Changes.

Hardware	Qty.	Added Weight (% of Total Engine Wt.)	Added Cost (% of Total Engine Cost)
Casing	1	0.50	1.36
Shroud Support	1	0.13	0.08
Manifold	1	0.19	0.20
Piping	-	0.07	0.10
Controls			
- Controls & Sensor	1	0.07	0.80
- Actuator & Valve	2	0.17	1.00
- Fuel Lines	-	0.03	0.10
		+1.17%	3.64%

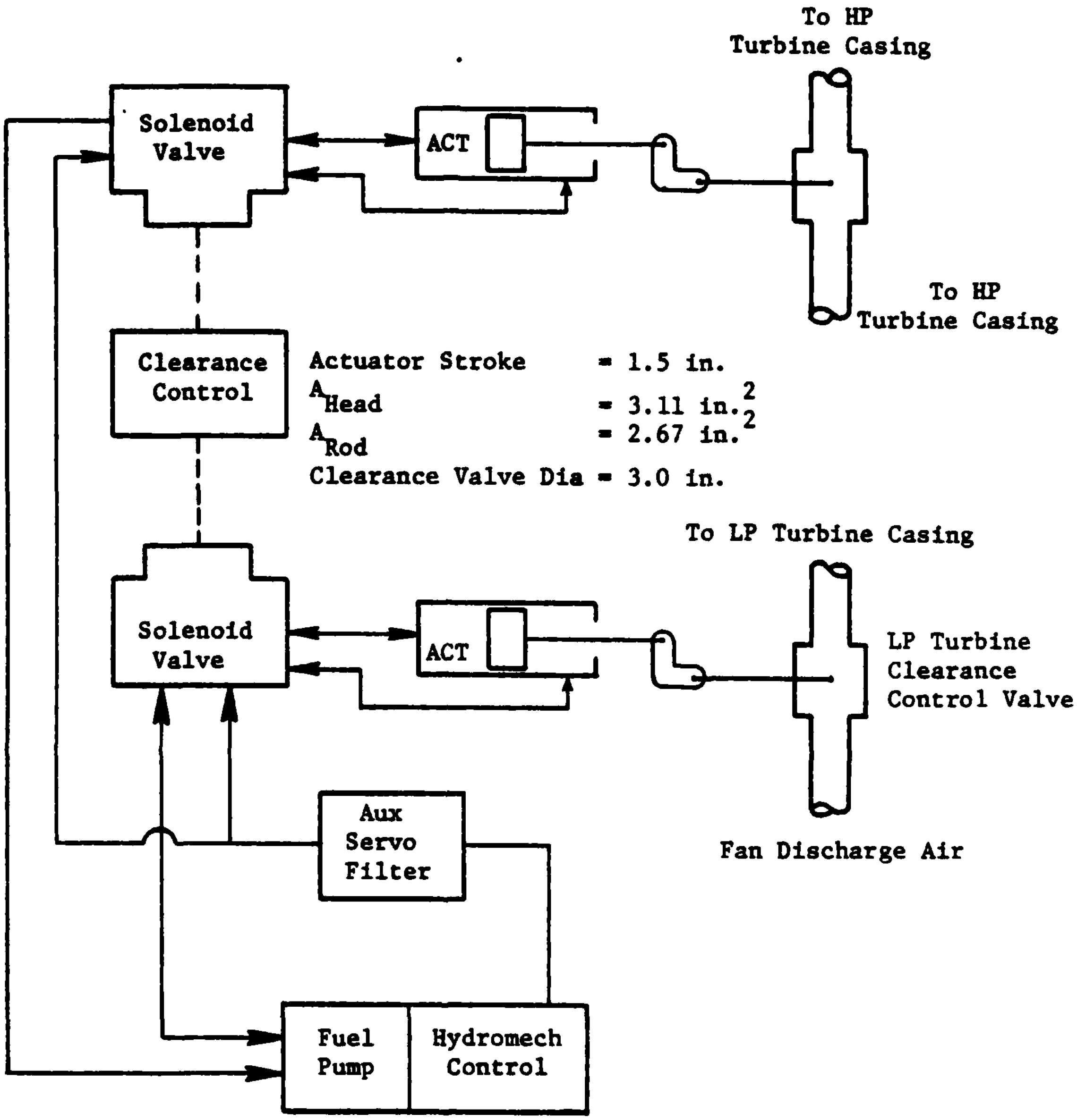

Figure 53. CF6-6 Engine Turbine Clearance Control System.

3.3.4.1 LP Turbine Considerations

Data on the responsiveness of CF6-6 low pressure turbine (LPT) performance to clearance improvement was available from other prior programs and was evaluated from a system payoff standpoint for comparison with the HPT payoff.

The LPT ACC configuration employed was an external fan air cooling system similar to the HPT configuration already evaluated. Through the use of the valve-controlled flow of the fan air through a tubular manifold, cooling air was impinged during the cruise mission leg upon the hot LPT casing at strategic points over ring support points of the LPT shroud/seals. Radial shrinkage of the rings was achieved resulting in reduced LPT blade-to-shroud clearance.

From previous program results the use of fan air in this manner resulted in a Δsfc benefit of 0.4%. The hardware modifications needed to direct and control this cooling air resulted in penalties of +0.82% cost and +0.62% additional weight. Summing these factors into a net DOC evaluation gave the following result.

$$\underset{(LPT)}{\Delta DOC} = 0.364\ \Delta sfc + 0.022\ \Delta WT + 0.085\ \Delta COST$$

$$= -0.146 + 0.0136 + 0.070 = -0.062\%$$

(Benefit)

This compares with -0.099% ΔDOC for the HPT ACC system.

4.0 COMPRESSOR

The F101/CFM56 and CF6 are good examples of modern, high efficiency axial compressors. To evaluate the benefits of ACC, work was carried out first on concept analysis and then heat transfer design and analysis of the selected concepts, followed by a payoff study.

4.1 F101/CFM56 COMPRESSOR

4.1.1 Concept Analysis

In axial-flow, high pressure compressors, efficiency and stall margin are extremely important performance parameters. To maximize efficiency and stall margin in the aft stages, it is necessary to minimize rotor blade-to-casing operating clearances. These clearances are set during transients by the centrifugal and thermal growths of the rotor combined with the thermal response of the casing. Cruise clearances usually increase because core speed decreases and the rotor experiences less centrifugal stretch. This results in decreased efficiency and lowered stall margin.

In the past, special material selection for shrouds and casings have been made in order to reduce the amount of clearance required during transients. This type of passive clearance control, however, has only a small effect on minimizing cruise clearances. A means of active clearance control must be developed to accommodate transient operation, yet provide small clearances at cruise.

The feasibility of incorporating active clearance control on the aft compressor case of the F101 and CFM56 engines and on the aft stages of the CF6-6 engine was studied.

The F101 and CFM56 engines have compressors which are very similar in design; the major differences being in material selection (Figure 54). The aft cases for which clearance control methods are most effective are both decoupled from the forward casing and supported by a wishbone structure. Air is bled at the leading edge of the Stage 6 rotor through a circumferential slot between the forward and aft cases. This air, which is used for turbine frame cooling, is an excellent source for cooling the aft case to reduce clearances during engine cruise settings. In addition, CDP air can be used as a source for heating the aft case to prevent rotor rubs during transients. Several concepts were identified which utilize various heating and cooling sources for clearance control. In the first, a mechanical system which utilizes a sliding valve to direct 5th stage bleed air across the aft case is shown in "ON" and "OFF" modes in Figures 55 and 56, respectively. In another concept (Figure 57), a valve is positioned to direct CDP air across the aft case with the air being re-ingested at Rotor 6 inlet. A third concept involves an external piping system, which also uses 5th stage bleed air for case cooling, is shown on Figure 58 with "ON" and "OFF" modes presented on Figures 59 and 60. Also evaluated was a piping system that utilized both 5th

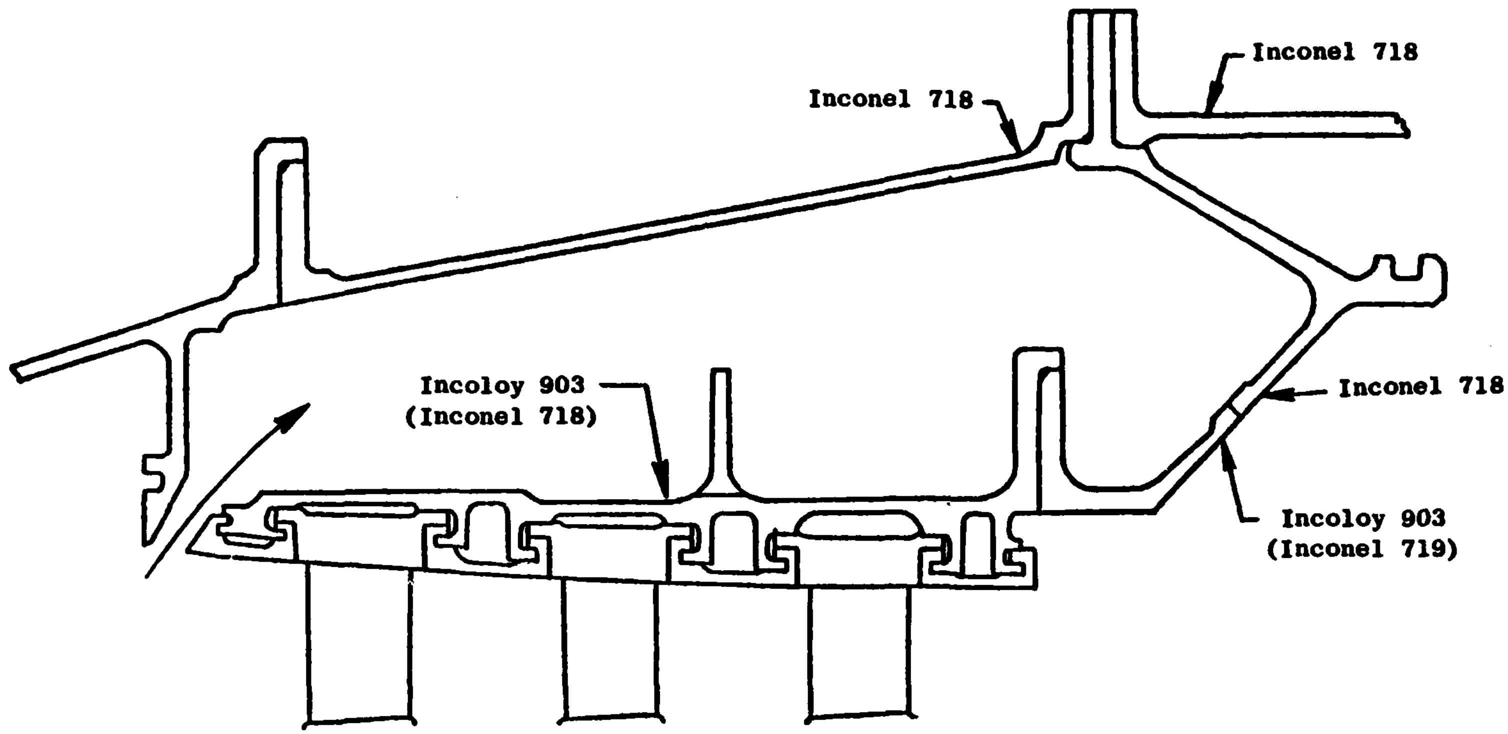

Figure 54. CFM56 (F101) Compressor Casing Materials.

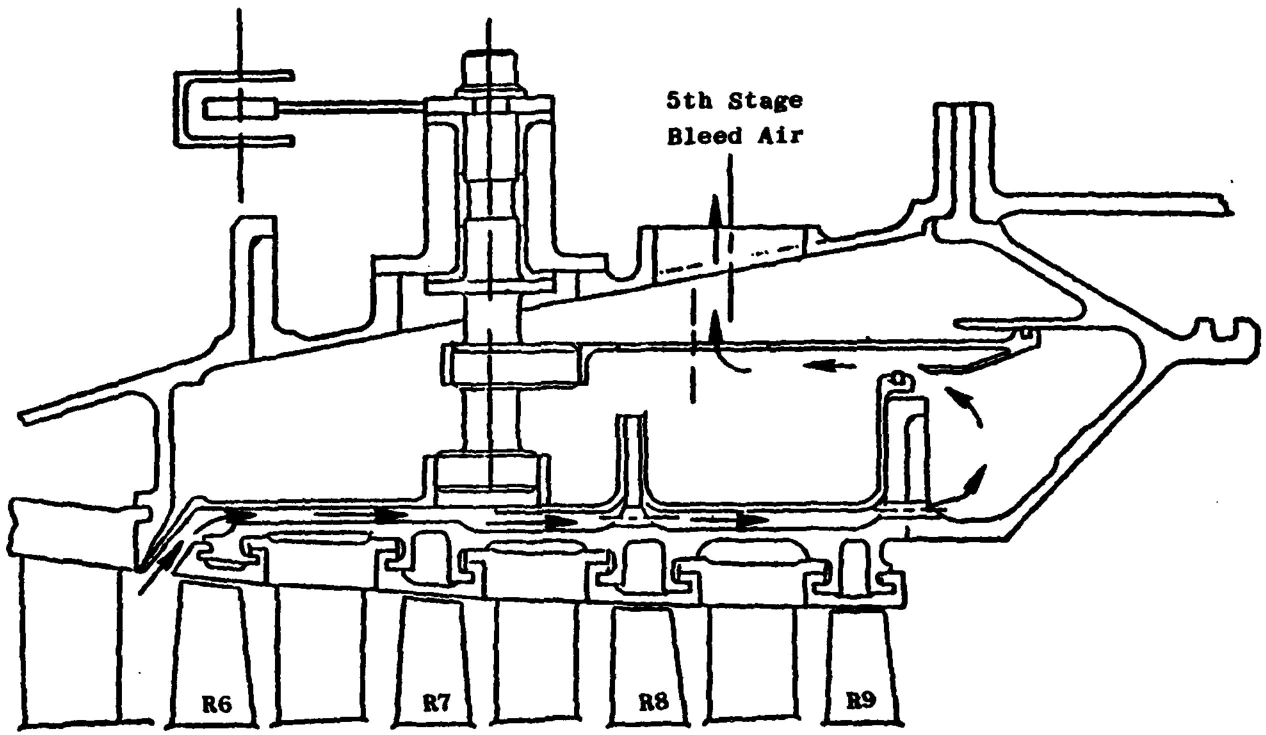

Figure 55. F101/CFM56 Clearance Control Mechanical System 5th Stage HPC Bleed System On-Cooling.

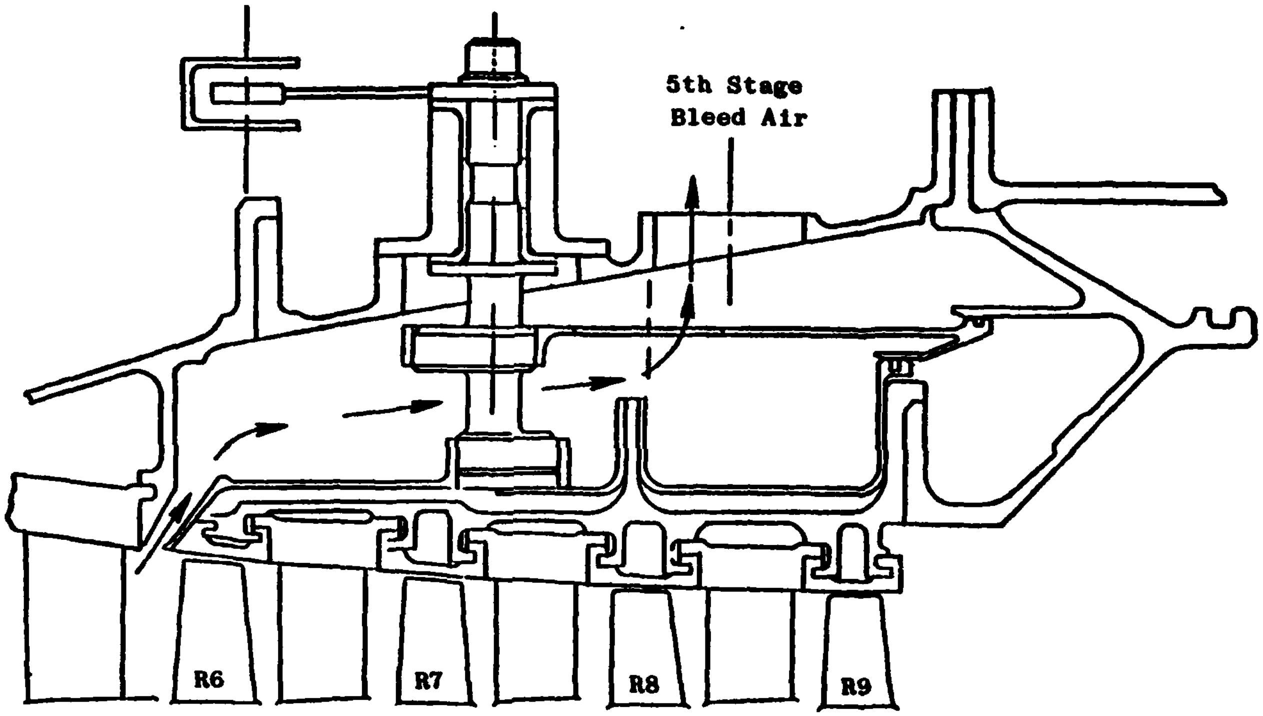

Figure 56. F101/CFM56 Compressor Clearance Control Mechanical System 5th Stage Bleed System Off-Bleed Bypass.

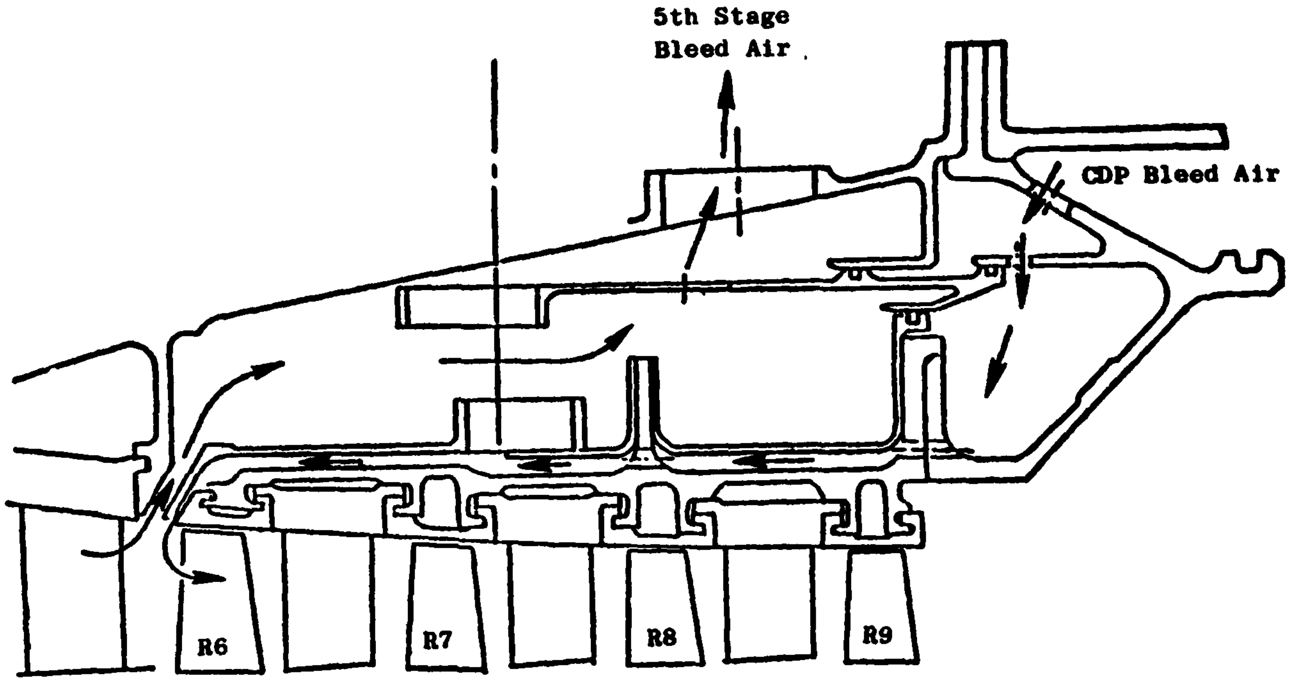

Figure 57. F101/CFM56 Rear Compressor Dual Flow Active Clearance Concept, CDP Heating Mode.

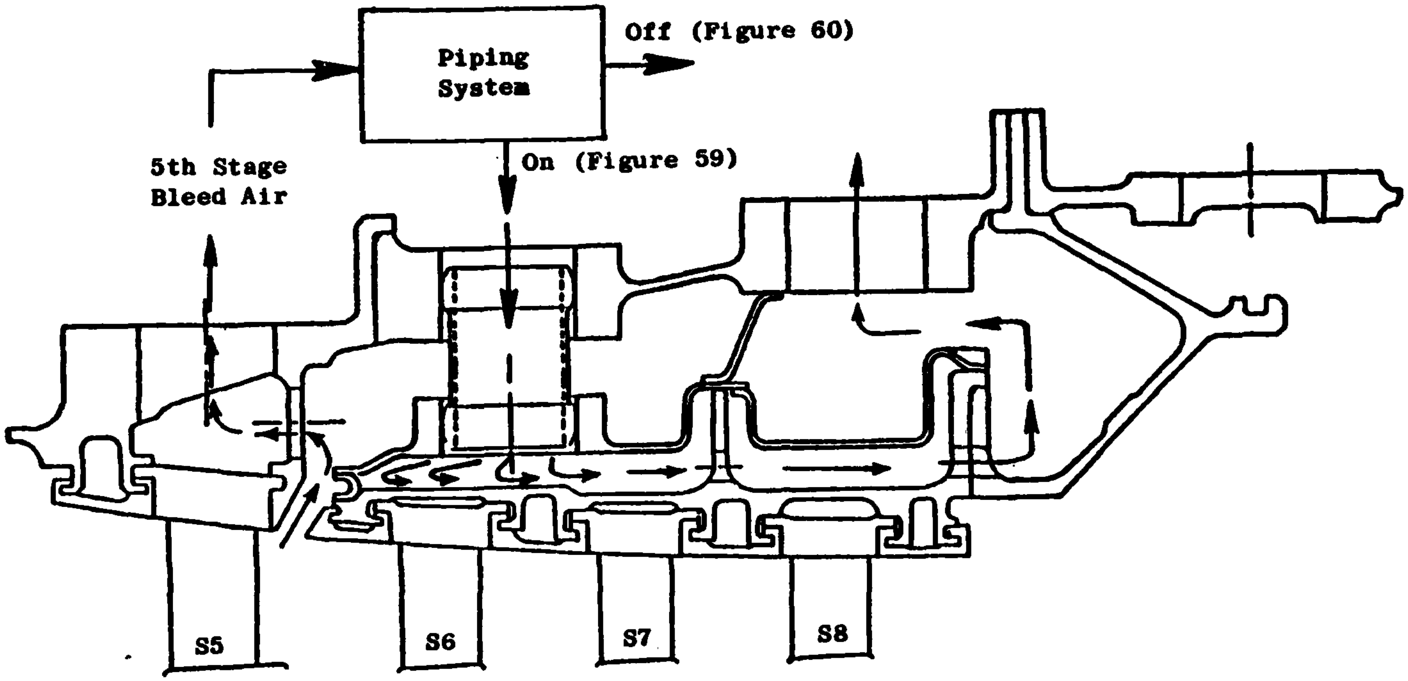

Figure 58. F101/CFM Rear Compressor Convection Piping Cooling Configuration.

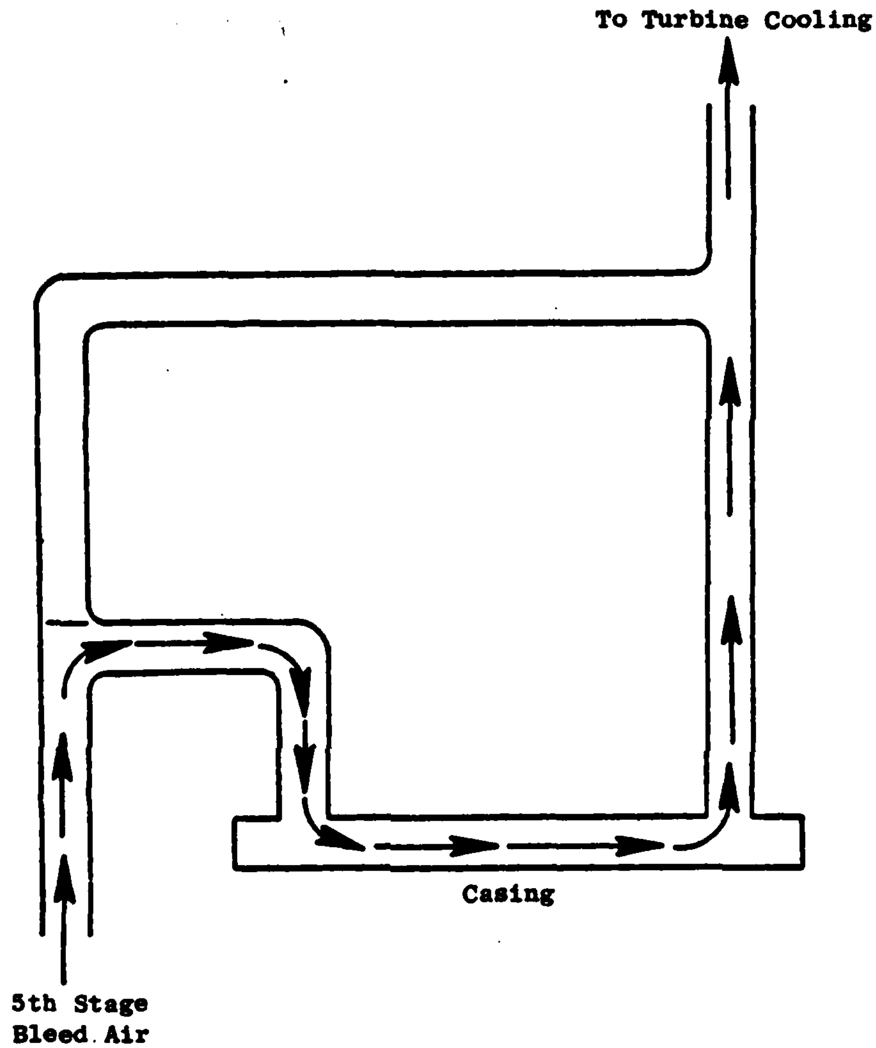

Figure 59. F101/CFM Compressor Piping System On - 5th Stage Cooling.

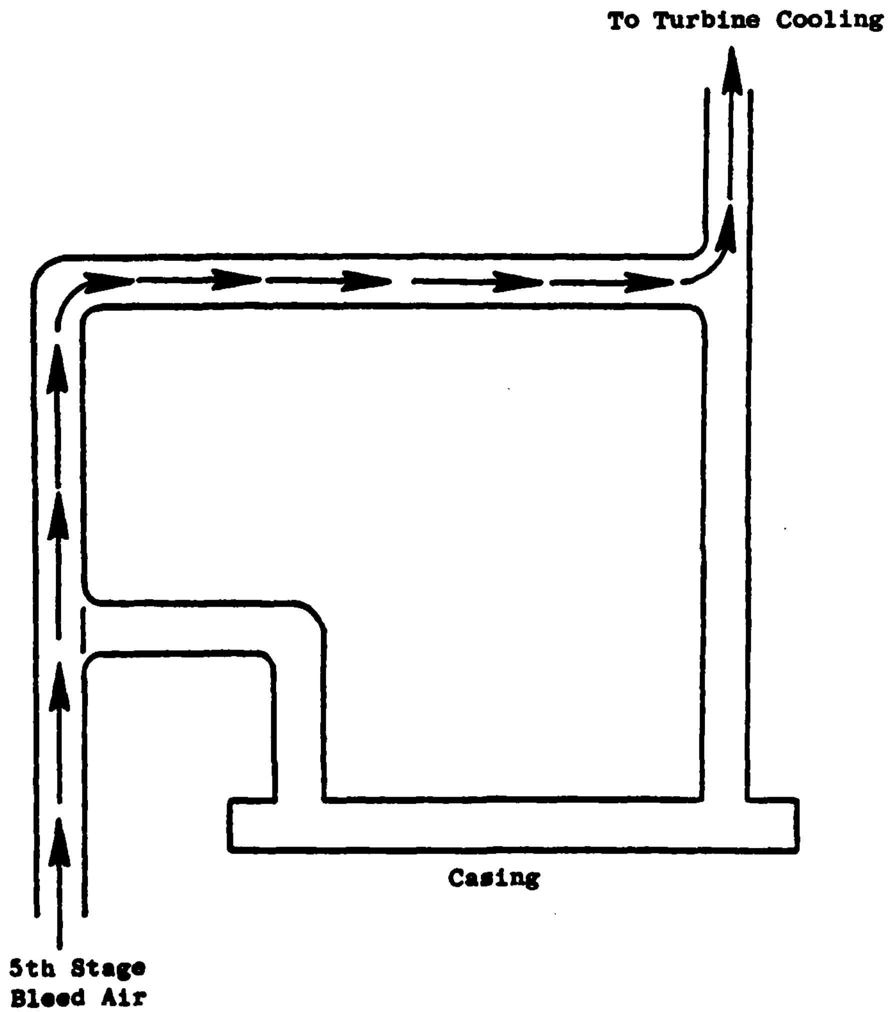

Figure 60. F101/CFM Compressor Piping System Off - 5th Stage Bypass.

stage and CDP bleed airs for case cooling and heating. This system is presented on Figures 61 and 62. Its flow chart for 5th stage cooling is shown on Figure 63, and its flow chart for CDP cooling is shown on Figure 64. The weight, cost, and performance effects of each of these configurations were evaluated for the mission cycles selected in Section 2.4.

4.1.2 Heat Transfer Design and Analysis

Compressor clearances were calculated for various percentages of bleed flow for each of the selected mission cycles (Section 2.4). Typically, thermal analysis of a casing was conducted utilizing the THTD computer program and primary and bleed flow data from the mission cycle. Results of the thermal analysis were input into the CLASS/MASS computer program to calculate casing growths as a prelude to determining rotor/stator clearances for that mission cycle and bleed flow.

Existing computer models of the F101 and CFM56 aft compressor case and support structure were utilized in these analyses. The THTD and CLASS/MASS models are shown in Figures 65 and 66, respectively. The effects on Δsfc of varying bleed flow were calculated using equations and constants explained in Section 2.4. These results are plotted on Figures 67 through 74. A sample calculation of the Δsfc determination is shown below, for the case represented in Figure 68.

Sample Calculation: F101 Bomber 5th Stage Cooling and CDP Heating

Equation:

$$\Delta SFC = KETA\ [(KCL*\Delta CL)_{ROTOR} + (KCL*\Delta CL)_{STATOR}] + [(KBL)_{5th\ STAGE} + (KBL)_{CDP}]\ \Delta BL$$

$$\Delta SFC = -0.592\ [(0.0112 \times 44.395)_{ROTOR} + (0.0056 \times 37.195)_{STATOR}] + [(0.274)_{5th\ STAGE} + (0.605)_{CDP}]\ \ 0.31$$

$$\Delta SFC = -\ \underline{\underline{0.145\%}}$$

Thus for an average rotor/stator clearance of $(44.395 + 37.195)/_2 = 40.795$ and bleed flow of 0.31% 5th stage and CDP bleed, Figure 68 shows the F101 would improve by 0.145% Δsfc.

For the AWACS application of the CFM56 a compressor clearance control system is required and is shown in Figure 75. It will use the same logic as the turbine clearance system, hence only a case temperature sensor will be required. Cost of the actuator and clearance controls valve has been included in the compressor design study.

Based on the Phase I and II control studies discussed earlier, the system selected for the CFM56 and F101 are similar and are described in Table 17.

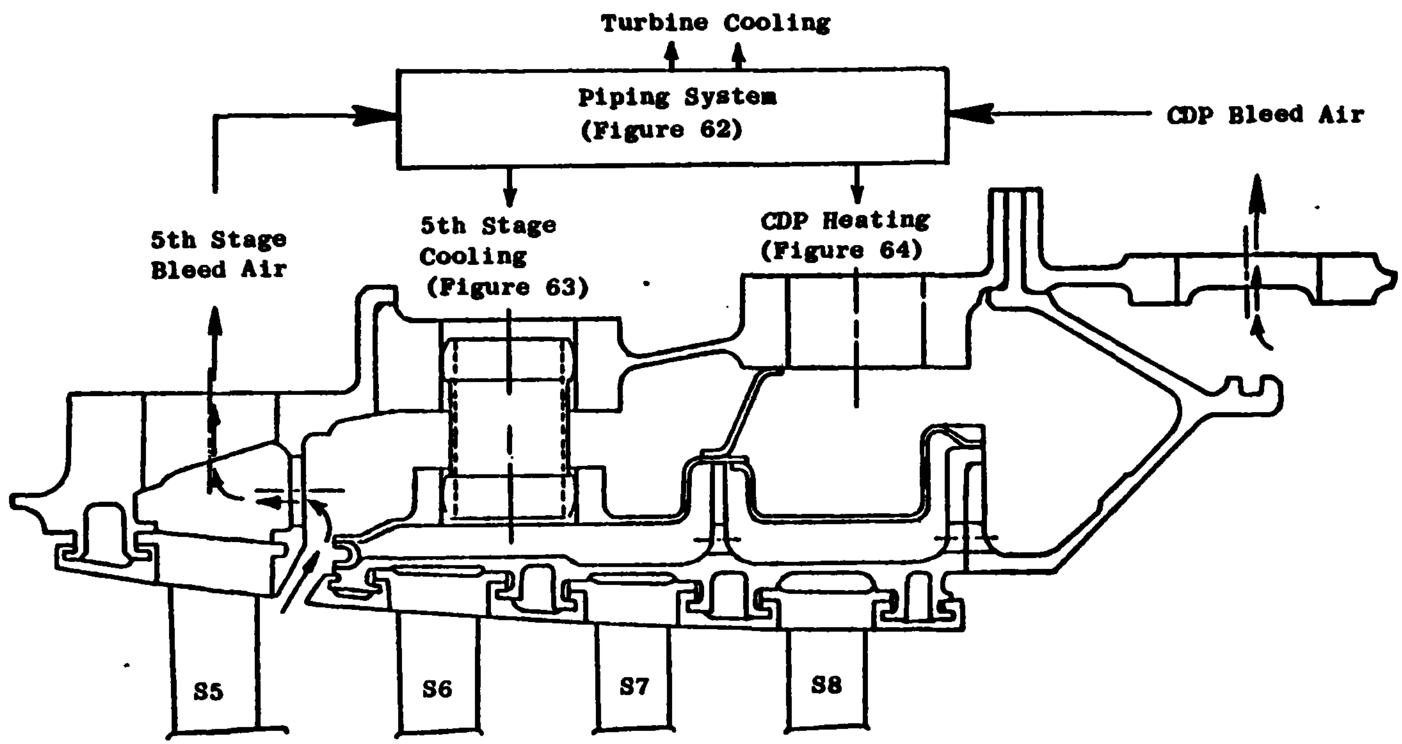

Figure 61. F101/CFM Rear Compressor Convection Cooling and Heating Configuration.

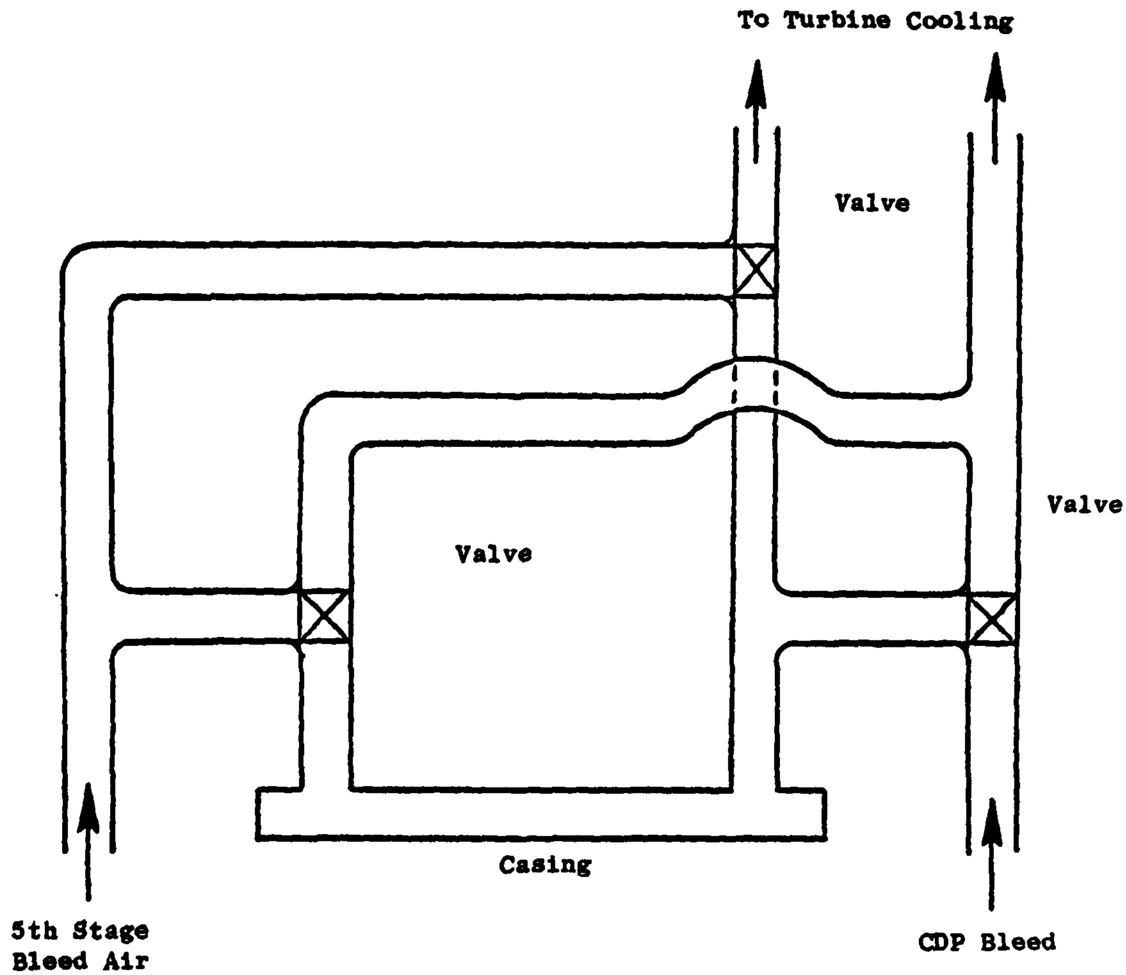

Figure 62. F101/CFM56 Compressor Clearance Control System External Piping 5th Stage Cooling and CDP Heating.

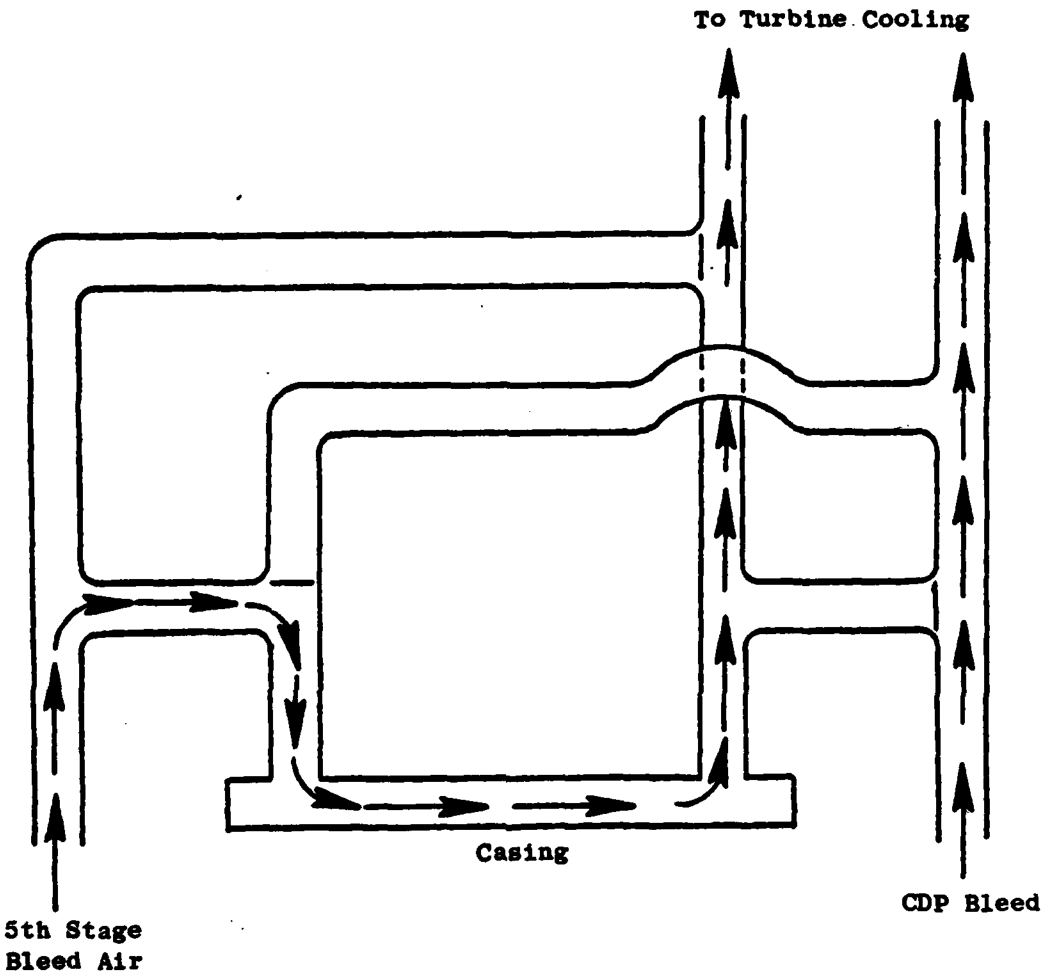

Figure 63. F101/CFM56 Compressor System On - 5th Stage Cooling.

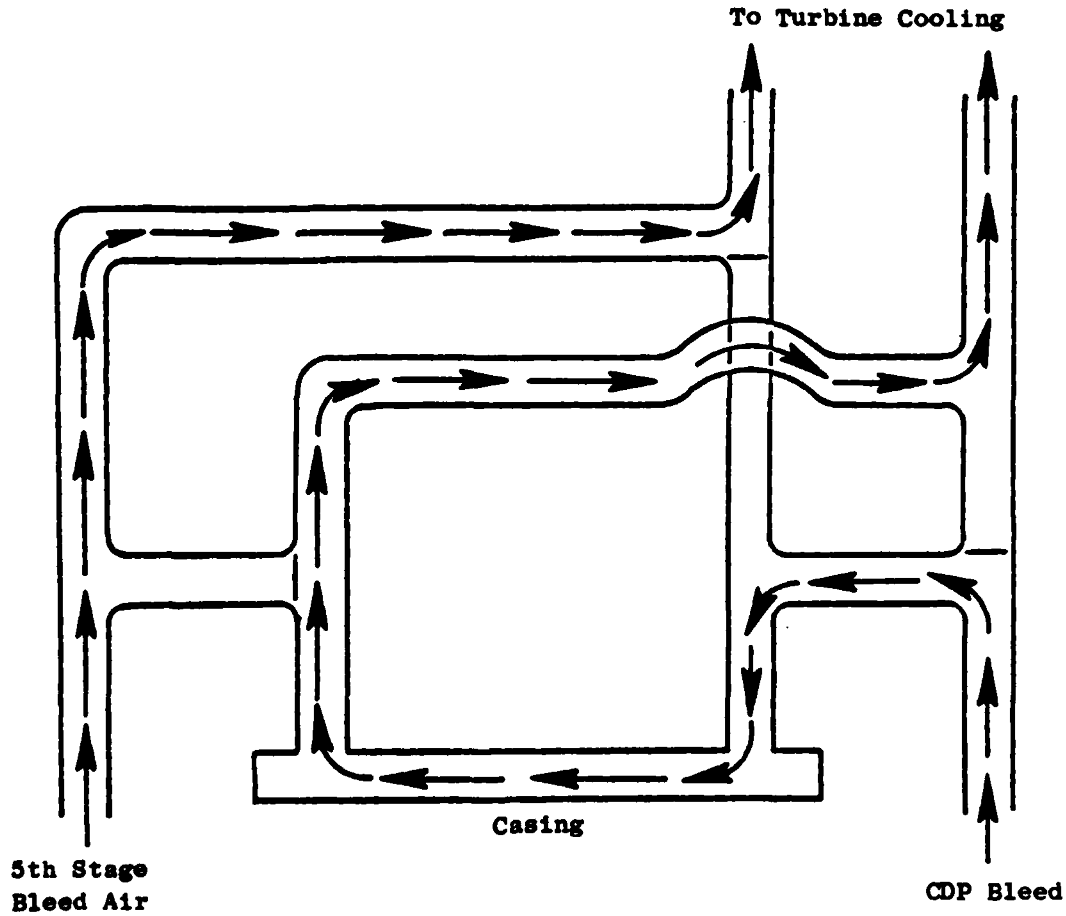

Figure 64. F101/CFM56 Compressor System On - CDP Heating.

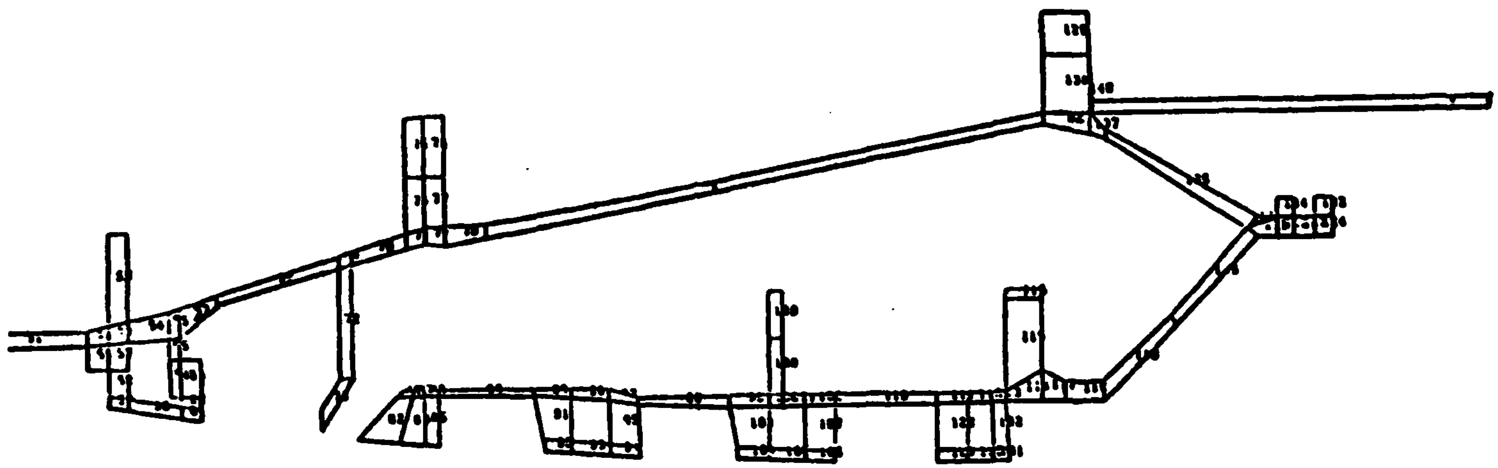

Figure 65. CFM56/F101 Rear Compressor Computer Thermal Model (THTD).

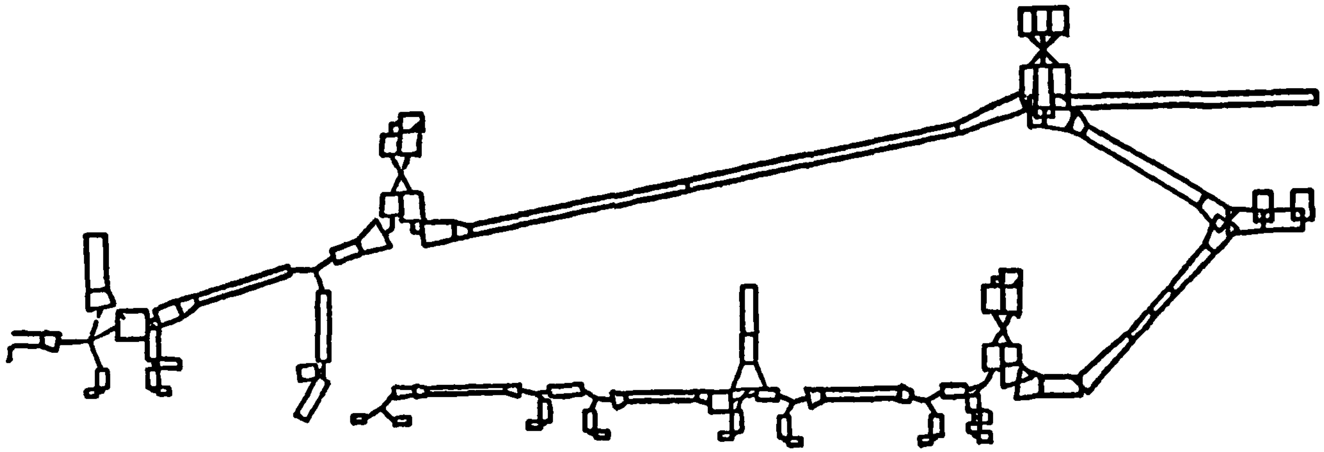

Figure 66. CFM56/F101 Rear Compressor Computer Deflection Model (CLASS/MASS).

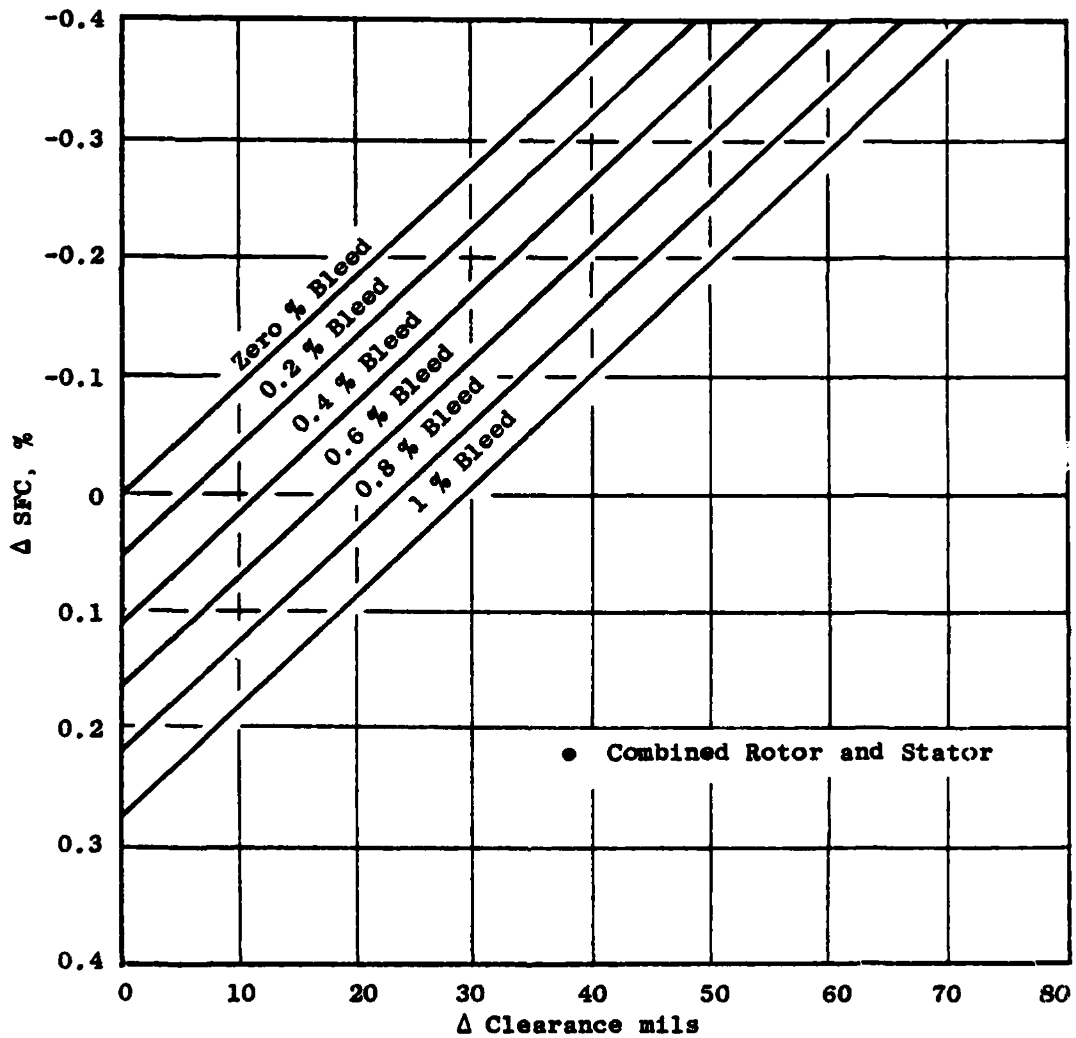

Figure 67. F101 Bomber HPC Clearance Control 5th Stage Cooling Mode Mechanical and Piping System.

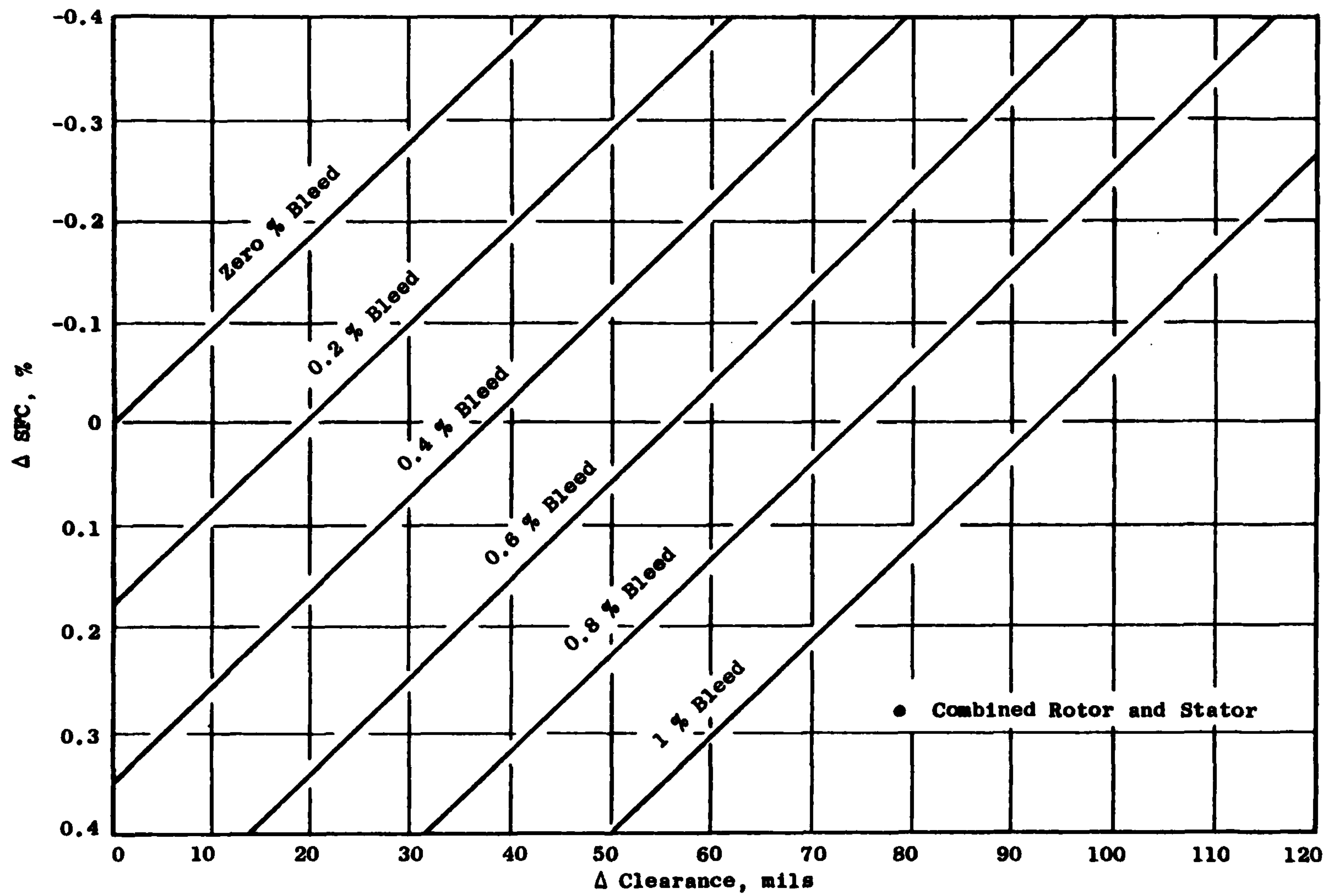

Figure 68. F101 Bomber HPC Clearance Control Combined 5th Stage Cooling and CDP Heating Mode Piping System.

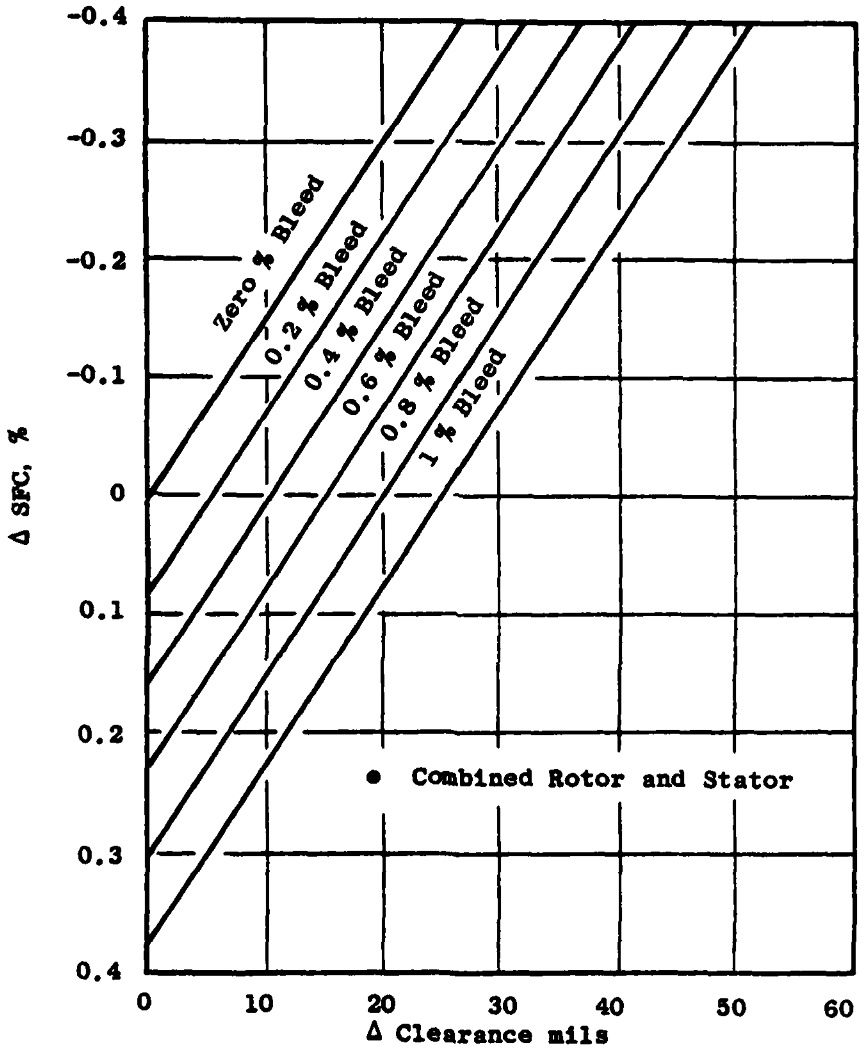

Figure 69. CFM Commercial HPC Clearance Control 5th Stage Cooling Mode Mechanical and Piping System.

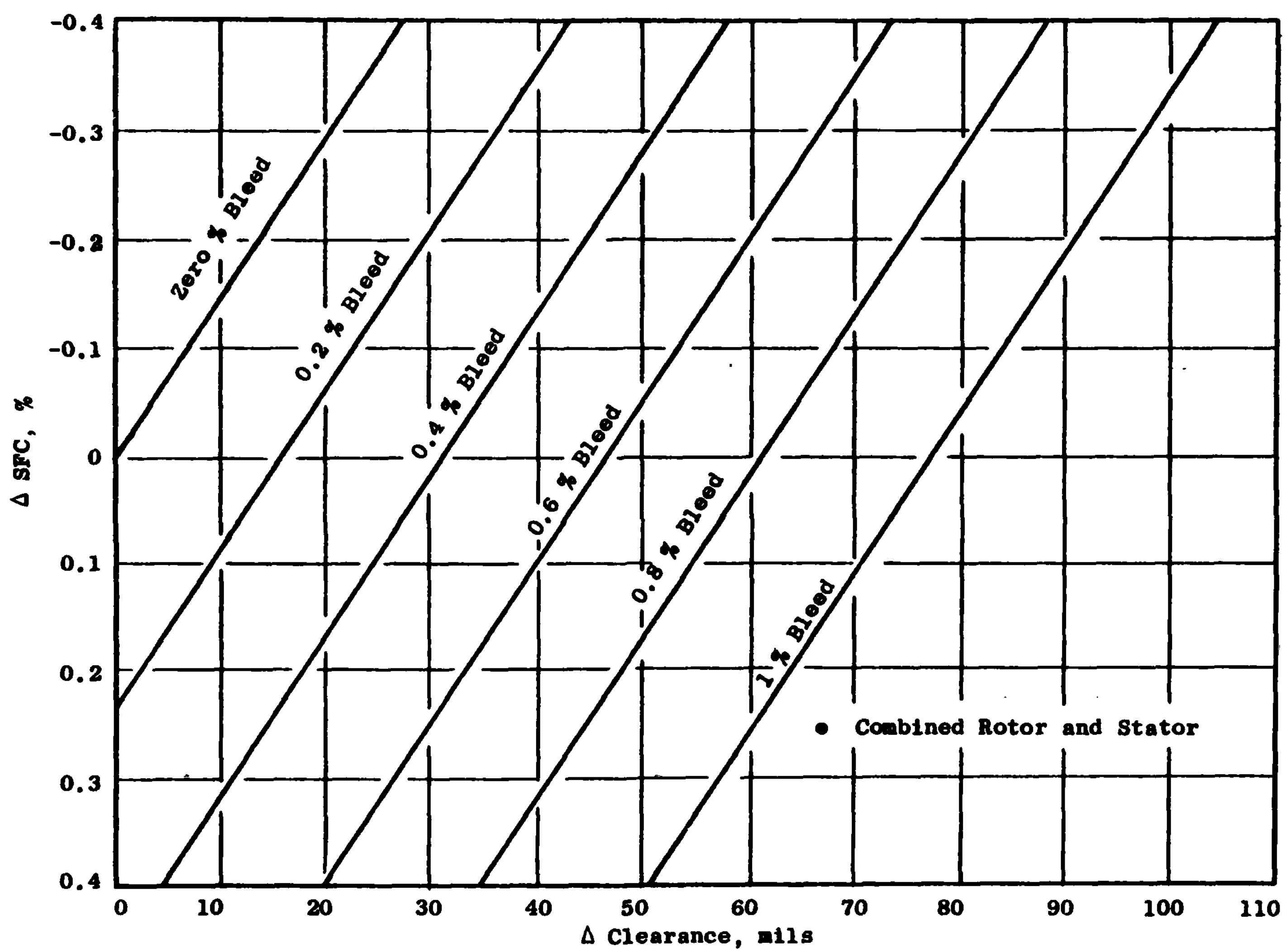

Figure 70. CFM Commercial HPC Clearance Control Combined 5th Stage Cooling and Heating Mode Piping System.

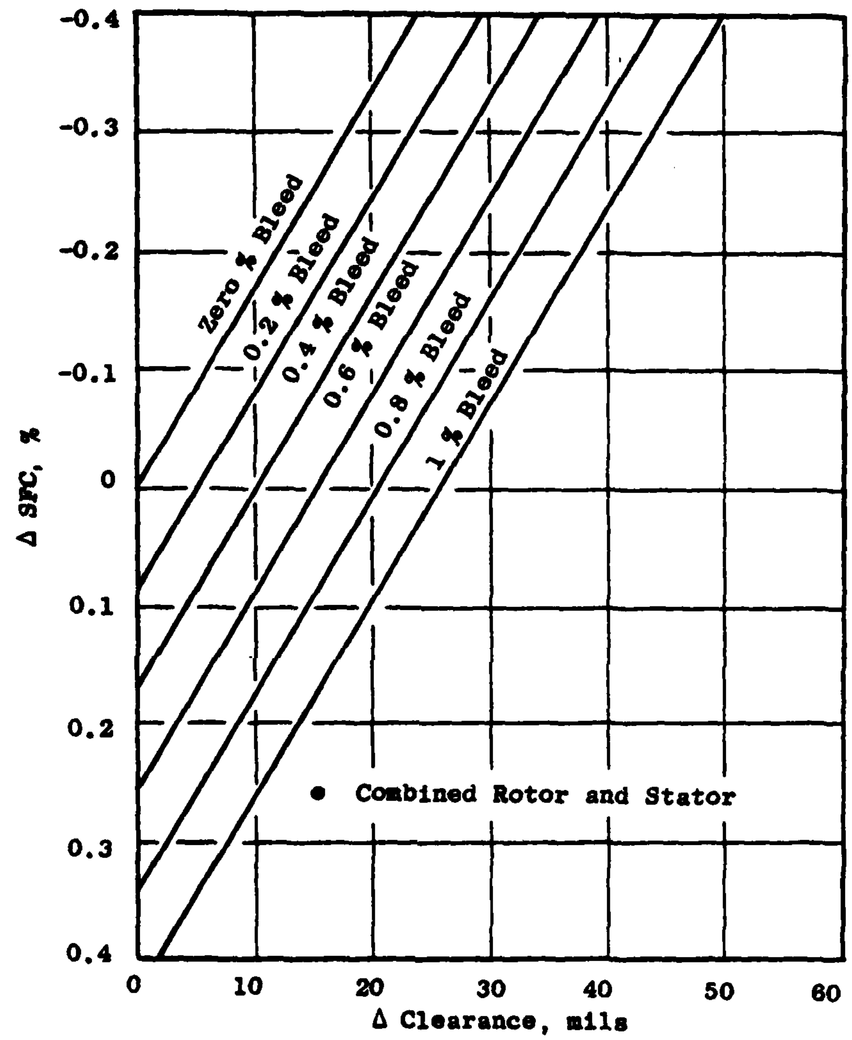

Figure 71. AWACS Loiter HPC Clearance Control 5th Stage Cooling Mode Mechanical and Piping System.

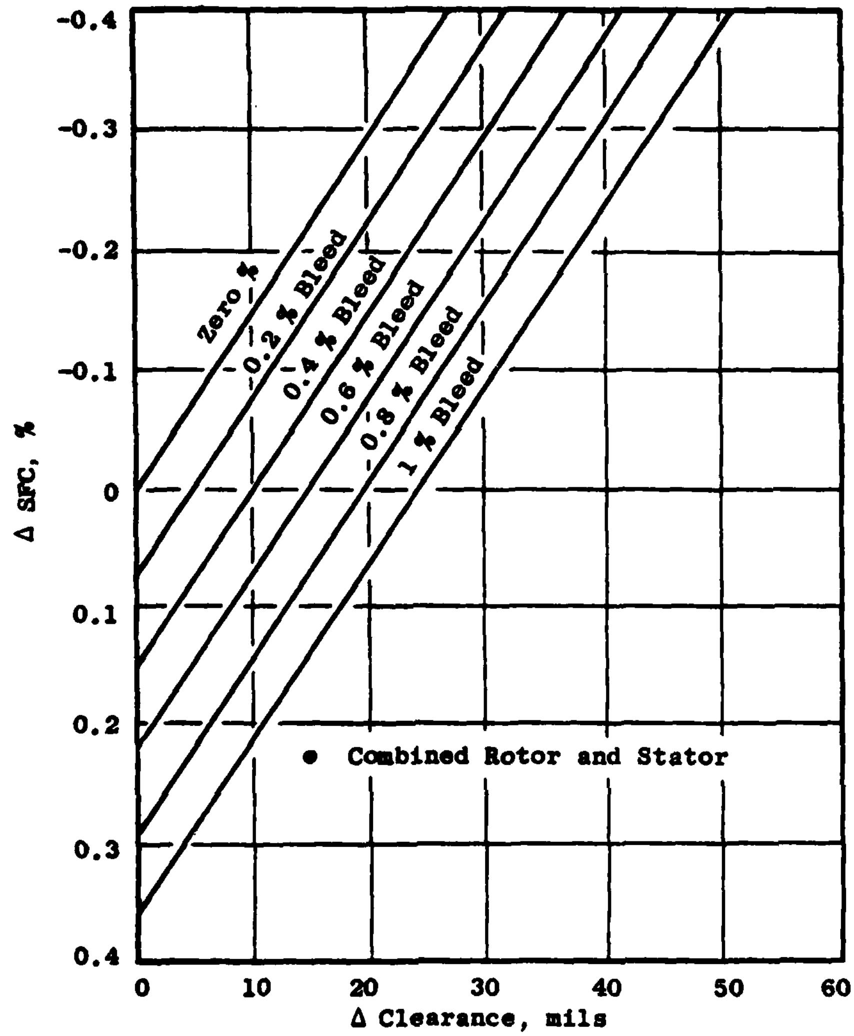

Figure 72. AWACS Cruise HPC Clearance Control 5th Stage Cooling Mode Mechanical and Piping System.

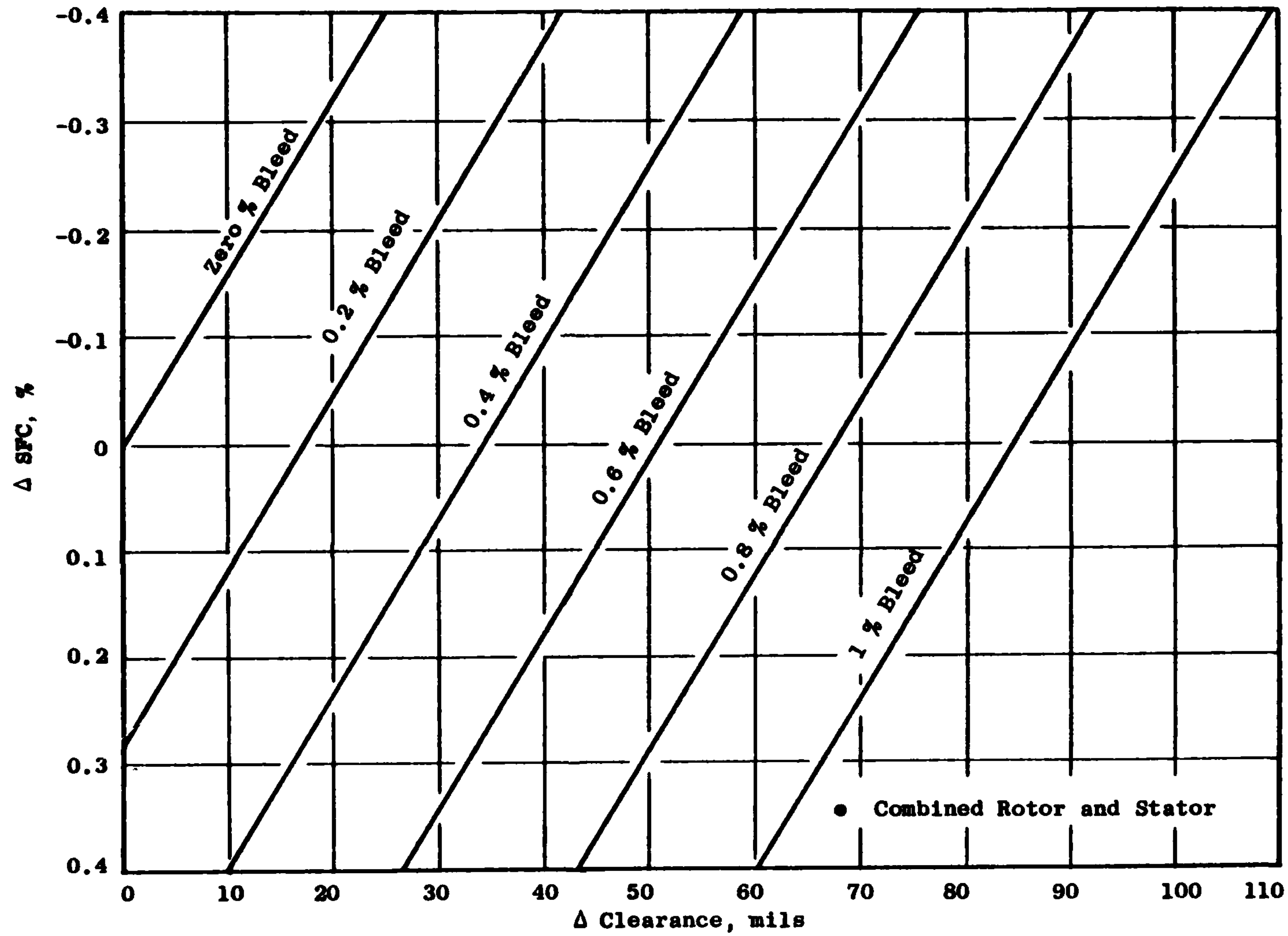

Figure 73. AWACS Loiter HPC Clearance Control Combined 5th Stage Cooling CDP Heating Mode Piping System.

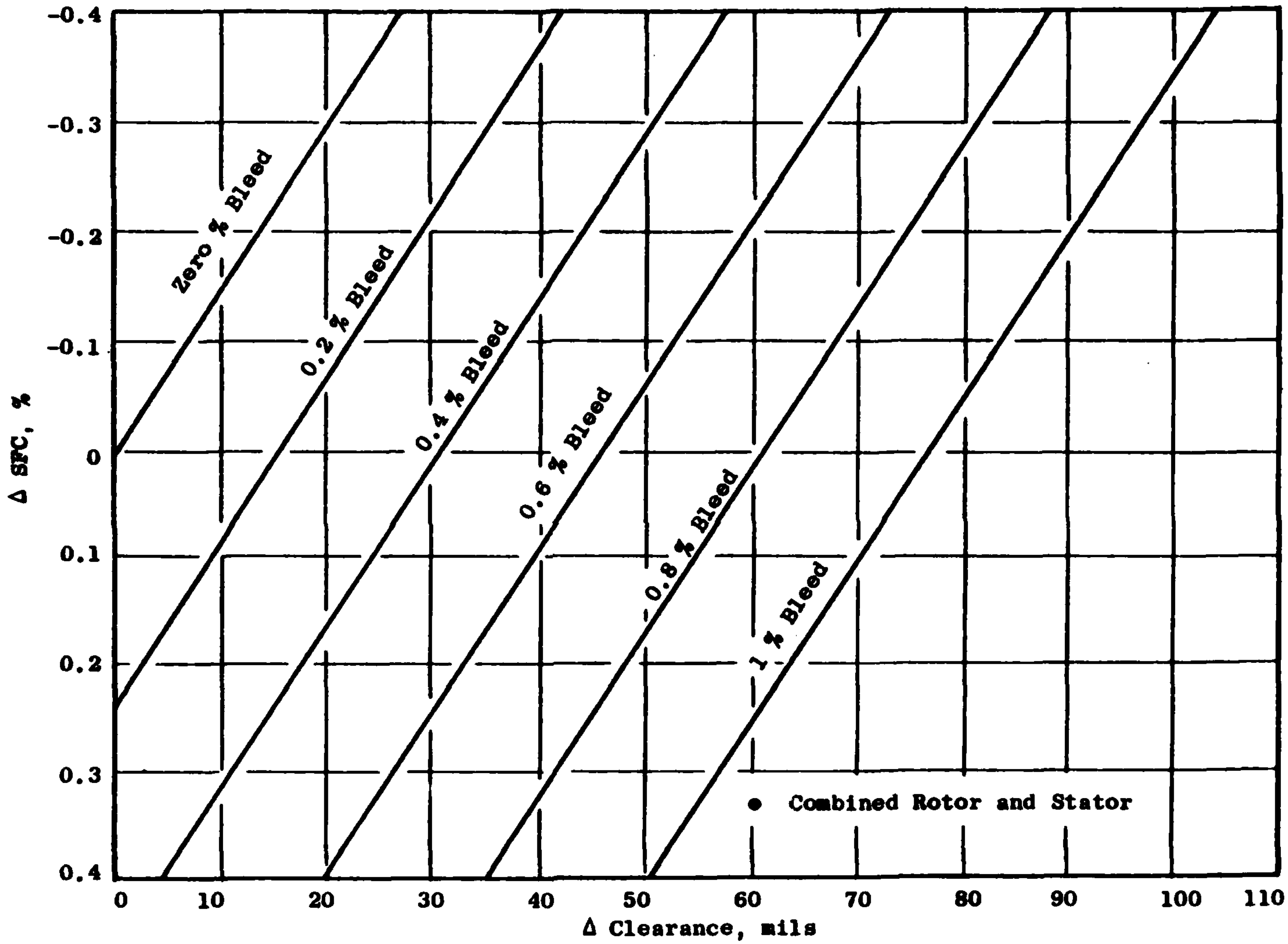

Figure 74. AWACS Cruise HPC Clearance Control Combined 5th Stage Cooling and CDP Heating Mode Piping System.

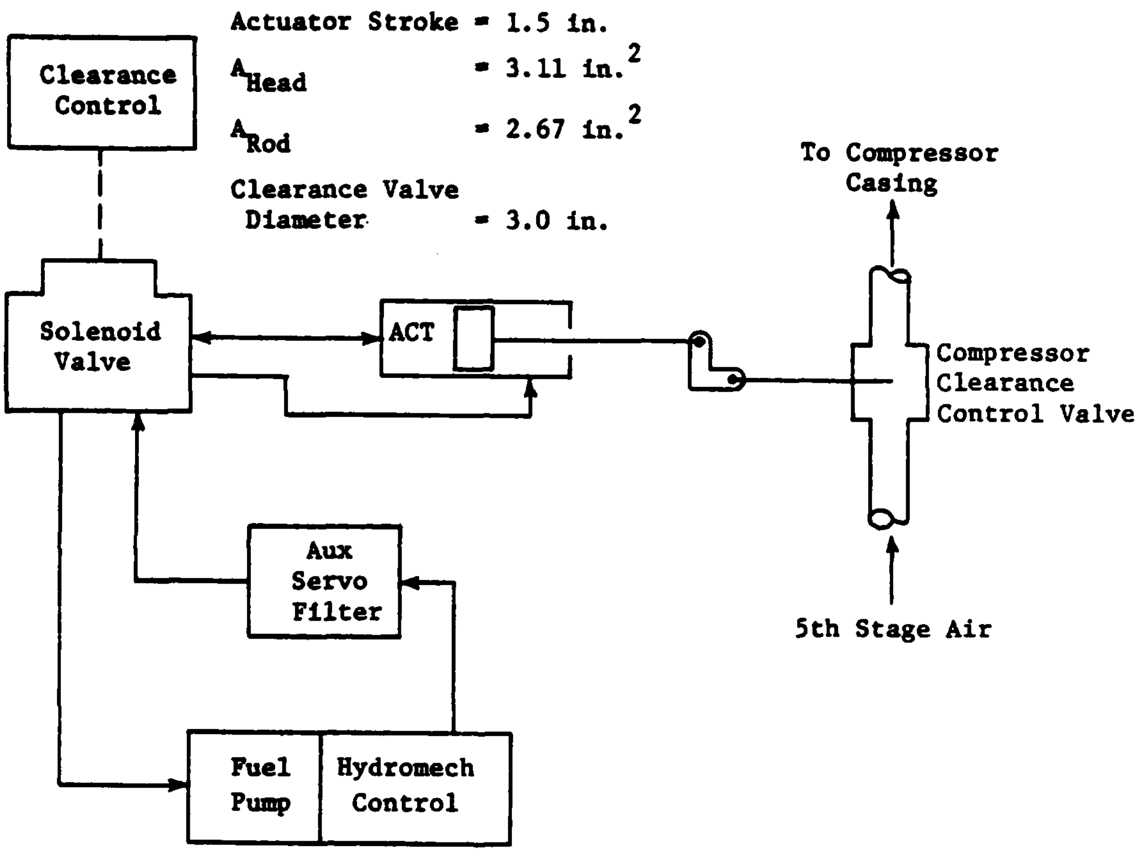

Figure 75. Compressor Clearance Control System CFM56 Engine.

Table 17. CFM56 and F101 Compressor C&A Requirements.

Engine	Air Supply System	Preferred Failure Mode	Flow (%W25) Min.	Flow (%W25) Max.	Supply Line Dia (In)	Control Logic	Actuation System
CFM56	5th Stage	Closed	0.3	0	3.0	Same as Turbine	Solenoid valve plus fuel powered actuator
F101	5th Stage	Closed	0.3	0	3.0	Same as turbine	Solenoid valve plus fuel powered actuator

4.1.3 Payoff Study

Weights and costs were generated for the mechanical and piping systems and are presented on Tables 18 and 19. These results, along with Δsfc results were used to calculate the aircraft sensitivity factors for each of the mission cycles. Results are listed on Table 20.

4.2 CF6-6 COMPRESSOR

4.2.1 Concept Analysis

The CF6-6, a high bypass ratio commercial engine, was studied for applications of compressor active clearance control systems. As discussed in Section 4.1, active clearance control concepts are most beneficial when applied to the aft stages of the compressor. This is due to the increased sensitivity of compressor efficiency to clearances because of shorter blade lengths.

The present CF6-6 compressor rear case, with its integral 13th stage bleed manifold, makes impingement cooling the most effective clearance control method (Figure 76). During cruise, a percentage of fan discharge air (engine station 2.5) is directed through small holes in cooling pipes onto strategic structural areas of the case (Figure 77). This causes the case to shrink thereby reducing rotor/stator clearances. The effect on Δsfc of extracting the bleed air required to achieve the proper clearance closure was evaluated.

4.2.2 Heat Transfer Design and Analysis

Heat transfer analyses of the CF6-6 rear compressor case was conducted utilizing the THTD computer program, the model for which is shown in Figure 78.

Table 18. CFM56/F101 Compressor ACC Modification Cost and Weight Changes.

Mechanical Cooling

Hardware	Qty.	Est. Weight (% of Total Engine)	Est. Cost (% of Total Engine)
Actuation Ring	1	0.078	0.167
Seal	1	0.203	0.125
Bosses	6	0.015	0.030
Support, Lever Arm	6	0.036	0.050
Bushings	12	0.011	0.010
Lever Arms	6	0.014	0.012
Shaft, Lever Arm	6	0.036	0.167
Shield, Casing	1	0.144	0.208
Actuators	2	0.068	0.333
Misc. (nuts, etc.)		0.604	0.023
*Totals		1.209%	1.125%

*The above costs and weights are based on F101/CFM hardware experience.

Table 19. CFM56/F101 Compressor ACC Modification Cost and Weight Changes.

Piping Cooling

Hardware	Qty.	Est. Weight (% of Total Engine)	Est. Cost (% of Total Engine)
Spoolies	4	0.007	0.033
Bosses	12	0.281	0.067
Manifolds	2	0.586	0.250
Pipes (1-1/2 x 0.028w)	8	0.027	0.017
Valve	1	0.198	0.275
Totals		+1.099	+0.642%

Piping Cooling and Heating

Hardware	Qty.	Est. Weight (% of Total Engine)	Est. Cost (% of Total Engine)
Manifolds	2	0.586	0.250
Valves	2	0.393	0.550
Pipes	4	0.014	0.008
Piping Cooling Totals		1.099	0.642
Totals		2.092	+1.450

Table 20. CFM56/F101 Compressor Modification Aircraft Sensitivity Factors.

	Mechanical Cooling	Piping Cooling	Piping Heating and Cooling
<u>F101 Bomber</u>			
ΔSFC (%)	-0.022	-0.022	-0.145
ΔWeight (%)	+0.605	+1.099	+2.092
ΔCost (%)	+1.125	+0.642	+1.450
ΔRange (%)	$\boxed{-0.035}$	-0.071	-0.094
<u>AWACS</u>			
ΔSFC (%) Cruise	-0.108	-0.108	-0.289
Loiter	-0.172	-0.172	-0.265
ΔWeight (%)	+0.614	+1.114	+2.120
ΔCost (%)	+1.125	+0.642	+1.450
ΔTime-On-Station (%)	$\boxed{+0.097}$	+0.012	-0.018
<u>Commercial CFM56</u>			
ΔSFC (%)	-0.095	-0.095	-0.292
ΔWeight (%)	+0.614	+1.114	+2.120
ΔCost (%)	+1.125	+0.642	+1.450
ΔDirect Oper. Cost (%)	+0.92	$\boxed{+0.055}$	+0.084

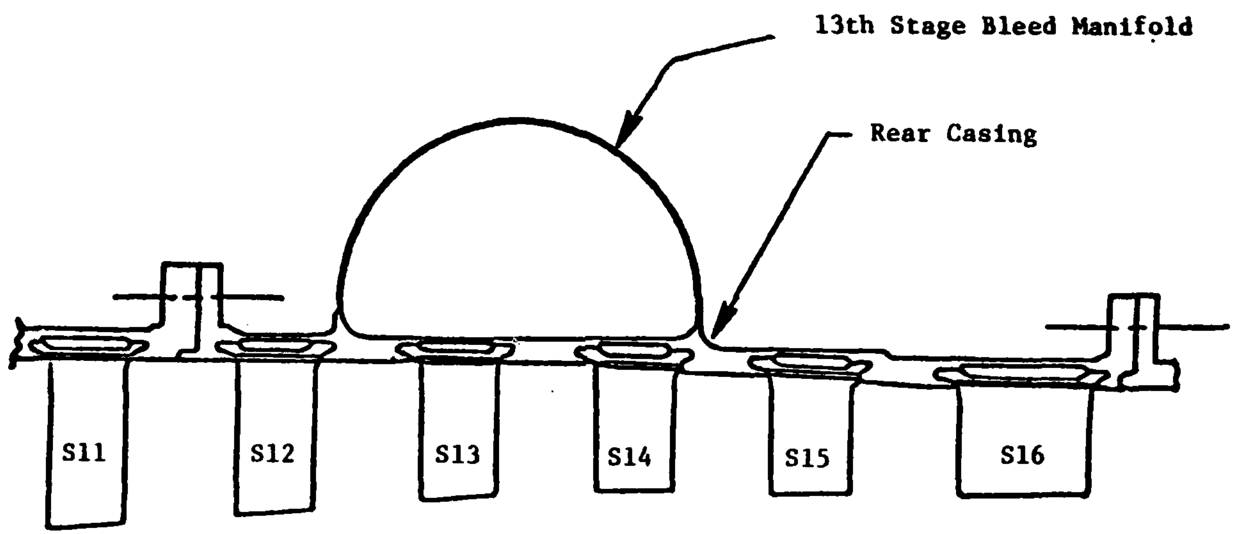

Figure 76. CF6-6 Rear Compressor Assembly.

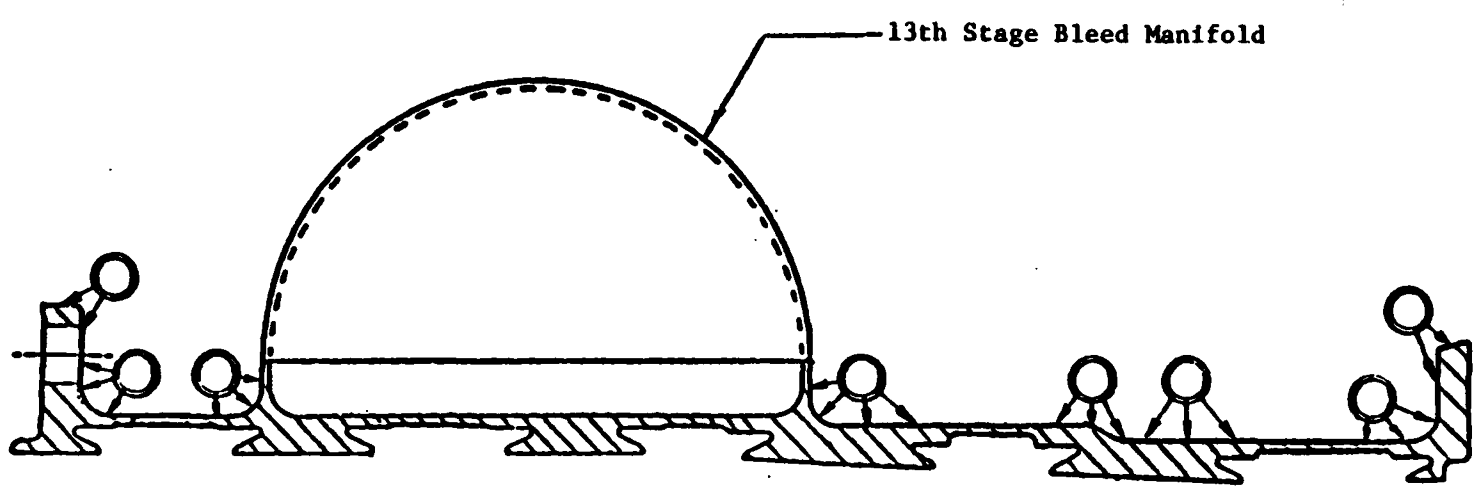

Figure 77. CF6-6 Rear Compressor Case Impingement Cooling Configuration.

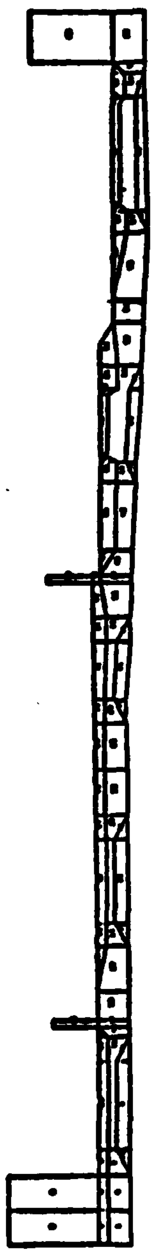

Figure 78. CF6-6 Rear Compressor Case THTD Model.

Flow conditions for the cruise mission (Section 2.4) were input into the model with the impingement areas shown in Figure 77 being subjected to 1% and 2% fan bleed air. Results from these runs were input into the CLASS/MASS computer model (Figure 79) to calculate casing deflections. From these results, reductions in rotor/stator clearances were determined. Using the payoff formulas and constants from Section 2.4, the effects on Δsfc of bleeding 1% and 2% fan discharge air were calculated.

A sample calculation of this Δsfc evaluation is shown below.

The average running clearance of the present CF6 compressor, as shown in Table 21, was used as a measure of the improvement in clearances that could be made. Then, using 1.0% fan air on the casing gave 107 mils total improvement in blade and vane clearances over 5 stages. The resulting Δsfc improvement was:

$$\Delta SFC = [KETA \times KCL \times \Delta CL] + [KBL * \Delta BL]$$

$$= [-0.824 \times 0.0088 * 107] + [1.903 * 1.0]$$

$$= +1.127\%$$

The summary of Δsfc results are shown in Table 22.

4.2.3 Payoff Study

As shown in Table 21, the use of any fan cooling air results in an increase in fuel consumption rather than the desired reduction. Thus no effort was spent evaluating weight or cost of the modified system.

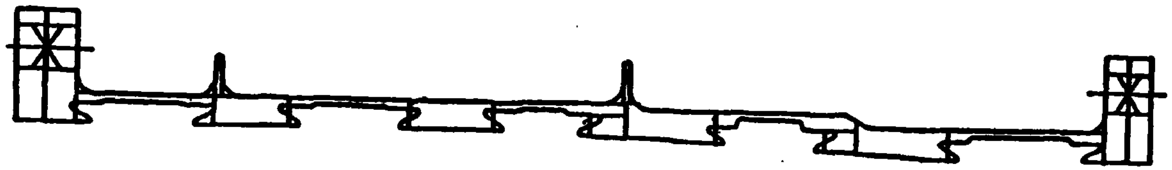

Figure 79. CF6-6 Rear Compressor Case CLASS/MASS Model.

Table 21. CF6-6 Compressor Average Cruise Running Clearances.

Stator (Rotor)	Blade-to-Case (in.)	Stage (Stator)	Vane-to-Spool) (in.)
12	0.013	12	0.035
13	0.028	13	0.046
14	0.037	14	0.046
15	0.035	15	0.037
16	0.023		
	0.136		0.164

- New engine clearances - 136 + 164 = 300 Mils total
- Clearances open up during stall
- Largest clearance change occurs during maximum gross weight Takeoff flight testing. High inlet loads during test cause Ovalization and backbone bending of HPC casing

Table 22. CF6-6 Impingement Cooling Fan Discharge Air.

Fan Air ($\%W_{25}$)	Cumulative Clearance Change (5 Stages) (Mils)	ΔSFC (%)
1	107	+1.127
2	142	+2.776

5.0 CONCLUSIONS

The results of the clearance systems analysis showed that impressive cycle improvements could be achieved. These are listed for the various engines as follows:

Engine/Aircraft		Cycle $\Delta\%\ \eta$	Benefits $\Delta\%$ SFC
• CFM56/AWACS:	Compressor	0.283	0.277
	Turbine	1.785	1.812
	Combined	2.068	2.089
• F101/Bomber:	Compressor	0.245	0.145
	Turbine	2.405	1.950
	Combined	2.650	2.095
• CF6/Commercial:	Compressor	-	-
	Turbine	1.005	0.734
	Combined	1.005	0.734
• CFM56/Commercial:	Compressor	0.310	0.292
	Turbine	1.772	1.780
	Combined	2.082	2.072

These significant improvements in efficiency and fuel consumption show the large gains which are possible in the turbines, and also show the difficulty in achieving gains in the already efficient compressors without first improving out-of-roundness. When the two-stage CF6 turbine is compared with the CFM56 or F101 single-stage turbines, it is also clear that the higher base efficiency of the CF6 makes further efficiency gains more difficult than in the CFM56/F101.

Weighing the cycle benefits above against the cost and weight penalties incurred, results in the following net payoff benefits:

Engine/Aircraft	Figure of Merit	HP Compressor	HP Turbine
CFM56/707	Δ DOC	(No Benefit)	0.6%
CFM56/AWACS	Δ Time-on-Station	0.1%	2.2%
CF6-6/DC-10	Δ DOC	(No Benefit)	0.1%
F101/B-1	Δ Range	(No Benefit)	0.7%

The positive ΔDOC improvements identified are encouraging and indicate that the ACC concepts can bring about economic benefits as well as performance benefits. An assessment of the magnitude of the ΔDOC benefit must be weighed along with many other factors such as utilization of aircraft and return on investment. Each of these must be evaluated for the specific aircraft user. Current factors that are major considerations are the financial charges for investment and the price of fuel. It can be stated, however, that 0.1% ΔDOC is noteworthy and 0.3% or more ΔDOC is of considerable interest to commercial airframe manufacturers.

The same trends noted in $\Delta\eta$ and Δsfc are found in these net payoff benefits and are even more pronounced. An important factor that should be noted is that the DOC evaluation is based on 1977 aircraft operating cost factors. When fuel cost increases since that time and the projections of further fuel cost increases are considered, the DOC payoffs shown are definitely conservative. These cost trends are shown in Figure 80 and show that 1980 fuel costs are expected to be 116% higher than 1977 fuel costs.

Specific conclusions in the individual turbine and compressor areas are discussed below:

5.1 TURBINE

The results of the turbine clearance study confirmed the conclusions that significant clearance control improvements can be achieved in existing and new engine systems. The study also identified that each individual engine system has to be evaluated in terms of the degree of hardware modification as reflected in cost and weight penalties. The combined cost and efficiency considerations which go into a DOC evaluation are ever changing parameters with the cost of fuel constantly increasing. For this reason, the evaluation has presented turbine efficiency and engine sfc improvements separately from fuel DOC parameter.

As an example the CFM56/F101 engine stator structure lends itself to simple modification into a fan air cooling system and thus has small cost/weight penalties and good payoff. The sensitivity of the single-stage CFM56/F101 turbine also heavily weighted the clearance benefit.

By contrast, a two-stage turbine engine like the CF6 requires modifications for an ACC system which are more extensive, involving higher weight and cost penalties. The CF6 two-stage HP turbine base efficiency is high and so its fuel consumption is not as responsive to ACC system clearance improvements.

5.2 COMPRESSOR

The cost and weight effects of hardware changes required to implement the three proposed compressor clearance control schemes to F101/CFM56 engines were compiled and integrated with the Δsfc results to yield overall system performance effects for the three missions considered.

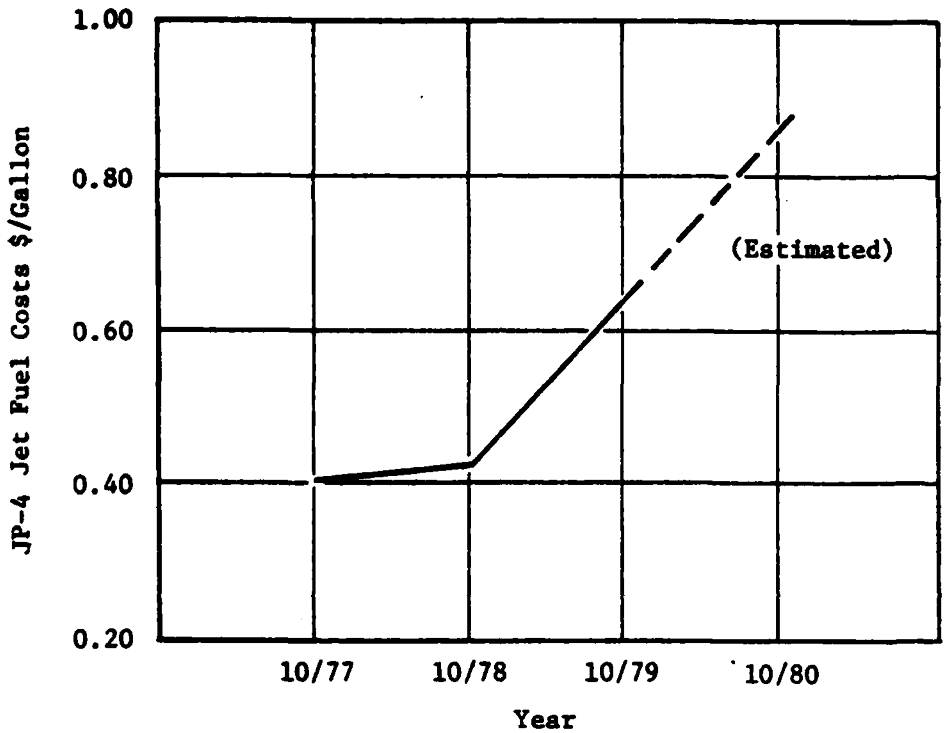

Figure 80. Recent Trend of JP-4 Jet Fuel Costs.

CF6-6

Clearance change effects on Δsfc were compiled for the CF6-6 impingement cooling of the rear compressor casing. The minimum total rotor/stator clearance reduction required for the cruise mission is 300 mils. From the results presented previously in Table 21, it is apparent that the required reduction cannot be accomplished without adverse effects on Δsfc. The conclusion is that impingement cooling of the CF6-6 rear case is not an effective means of controlling clearances. By comparison with CFM56/F101 results, ways to improve the CF6 clearance would be to utilize a double-wall casing. Also the reduction of casing distortion and ovalization due to "backbone" bending is a major improvement that is needed to allow utilization of ACC methods.

CFM56/F101

For the F101 bomber mission, the weight penalties associated with incorporating the three clearance control schemes overrode gains made in Δsfc yielding reduction in the mission range. In addition, it was recognized that in the mechanical valve system, the re-ingestion of CDP bleed air at the Rotor 6 inlet causes severe adverse effects in compressor stall margin. For this reason, this scheme was not considered as a viable clearance control method. For the CFM56 AWACS mission, the piping cooling system yielded slighty increases to the amount of time the plane could spend on station. Weight penalties for the piping heating and cooling system caused reduction in the time-on-station parameter. For the CFM56 commercial mission, weight and cost penalties caused an increase in direct operating costs.

5.3 OVERALL CONCLUSIONS

A listing of the significant conclusions of the overall study are as follows:

- HP turbine clearance payoff potential is much greater than in the HP compressor.
- Significant clearance improvements (0.016 to 0.025 inches) can be achieved, but offsetting system penalties are severe in all but the CFM56 commercial application.
- Fan Air cooling/clearance control is highly preferred where pipes and valving can be minimized.
- Single-stage HP turbines offer greater payoff than two-stage HP turbines.
- Retrofit of existing engines to achieve payoff is extremely difficult (i.e., weight and cost are prohibitive unless modifications are very simple).

- Basic engine roundness must be well established for clearance control systems to achieve their full potential.

- ΔDOC benefits may be increasingly attractive as fuel prices continue to climb. The conclusions of this study are based on 1977 aircraft operating cost factors.

6.0 RECOMMENDATIONS

The overall recommendations reflect the conclusions of the study and can be grouped into several basic categories as follows:

6.1 RETROFIT DESIGN

Consideration of retrofitting and active clearance system onto an existing engine must consider the following characteristics:

- Present clearances
- Sensitivity of efficiency improvement to reduced clearance
- Complexity of modifications required.

Some current engines may not show good payoff in response to ACC retrofit unless the modifications are kept very simple. This is due to the inherent transient characteristics of the particular configuration geometry which may have been dictated by other demanding considerations (i.e., stress, life).

On the other hand, even though deployment of a full ACC system to such engines may not have payoff, a partial ACC system using simple ACC concepts that require less extensive modifications may be well worthwhile.

6.2 NEW ENGINE DESIGN

The design of new engines should incorporate ACC consideration in the early stages of design. The most important part of this design work is the achievement of a good passive control system with (1) firm roundness control (ring stiffness) and (2) insensitivity to unsymmetric loading, and ease of adapting external thermal clearance control. Once these characteristics are "designed-in", attention can be devoted to innovative ways to apply ACC ducting, to sizing of geometry, and to incorporating accurate responsive control systems.

6.3 FURTHER WORK

Additional work is needed to better adapt control techniques to ACC. Remote systems (no direct clearance feedback) are heavy and expensive. Simpler cheaper controls must be designed or a reduction in the mission parameters must be made.

In the area of direct measurement controls, support should be given to the continued development of these concepts with the goal of flight demonstration in the near future.

Both of the turbine ACC designs studied show promise. The CFM56/F101 ACC concept is very attractive in the configuration studied. Any future Air Force utilization of these engines should include detail design and evaluation of an external fan air ACC system. Configuration modifications to the present design should be small yet significant performance improvements are possible.

The CF6-6 turbine ACC design also should be pursued in more depth. The ACC configuration offers significant advantages in the increased stiffness and roundness control of the basic casing and has been identified for follow-on work in an ongoing Government program. Emphasis should be placed on weight and cost reduction of the ACC modifications. This will allow more of the fuel consumption improvements to carry over into net system benefits.

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